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Evaluation of Training Samples Manually Welded With the Universal Handtool in a Space Simulation Chamber

C.K. Russell, T.W. Malone, and S.N. Cato
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May 2004

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LIST OF ACRONYMS AND SYMBOLS

Al	aluminum
Cu	copper
EBW	electron beam welding
Fe	iron
ISS	*International Space Station*
ISWE	International Space Welding Experiment
Mg	magnesium
Mn	manganese
PWI	Paton Welding Institute
Si	silicon
SS	stainless steel
UHT	universal handtool
Ti	titanium
U.S.	United States
V	vanadium

TECHNICAL MEMORANDUM

EVALUATION OF TRAINING SAMPLES MANUALLY WELDED WITH THE UNIVERSAL HANDTOOL IN A SPACE SIMULATION CHAMBER

1. INTRODUCTION

The universal handtool (UHT) is an electron beam welding (EBW) system that shows promise for repairing damaged structures on the *International Space Station* (*ISS*). This instrument consists of a handheld EBW tool, which operates at 8 kV with up to 1 kW of power. It was designed by the E.O. Paton Electric Welding Institute (PWI), Kiev, Ukraine. The international space welding experiment (ISWE) was designed to evaluate the UHT's primary functions, as well as to evaluate various weld joint configurations on typical materials used in space vehicles and demonstrate the UHT functions of brazing, coating, and cutting.[1] After ISWE was demanifested as a payload on the United States (U.S.) Space Shuttle, PWI made arrangements with the Russian Space Agency to accomplish its science objectives in space as an extravehicular activity from the Russian Space Station *Mir*.

ISWE was to be conducted by cosmonauts who were trained to properly operate the UHT and correctly process samples.[2] This Technical Memorandum discusses samples welded in a TBK–50 vacuum chamber in Russia from April to May 1998 (fig. 1). The processed samples were received at Marshall Space Flight Center in April 1999. Table 1 lists each sample by material, type, and name of the cosmonaut who processed it, as well as the manner in which it was processed; i.e., cut, welded, or brazed. Most samples were prepared on plate material to facilitate the extraction of mechanical test samples. Samples were prepared from five materials with thicknesses chosen based on the UHT's power capacity: Al 1100, Al 2219, Al 5456, 304 stainless steel (SS), and Ti–6Al–4V. Table 2 shows chemical compositions.

Tests were performed on two weld joint configurations, specifically a square butt joint, with and without joint gap, and a lap joint fillet weld. Plate samples were used to demonstrate cutting and bead-on-plate welds. Evaluations were conducted on two tube configurations; i.e., pin holes in Ti–6Al–4V tubes for plug welding and a 304 SS braze joint. Two samples were tested as being representative of damaged *ISS* component configurations—one for U.S. hardware and the other for Russian hardware.

The TBK–50 chamber was also used to test weld sample layout, ambient lighting requirements, validity of established weld parameters, effectiveness of protective spacesuit covering, and medical effects of the working conditions imposed by this experiment setup.[2] The operators trained in an Orlan suit similar to those used in space. The suit and UHT were equipped with counterweights for simulated weightlessness (figs. 2 and 3).

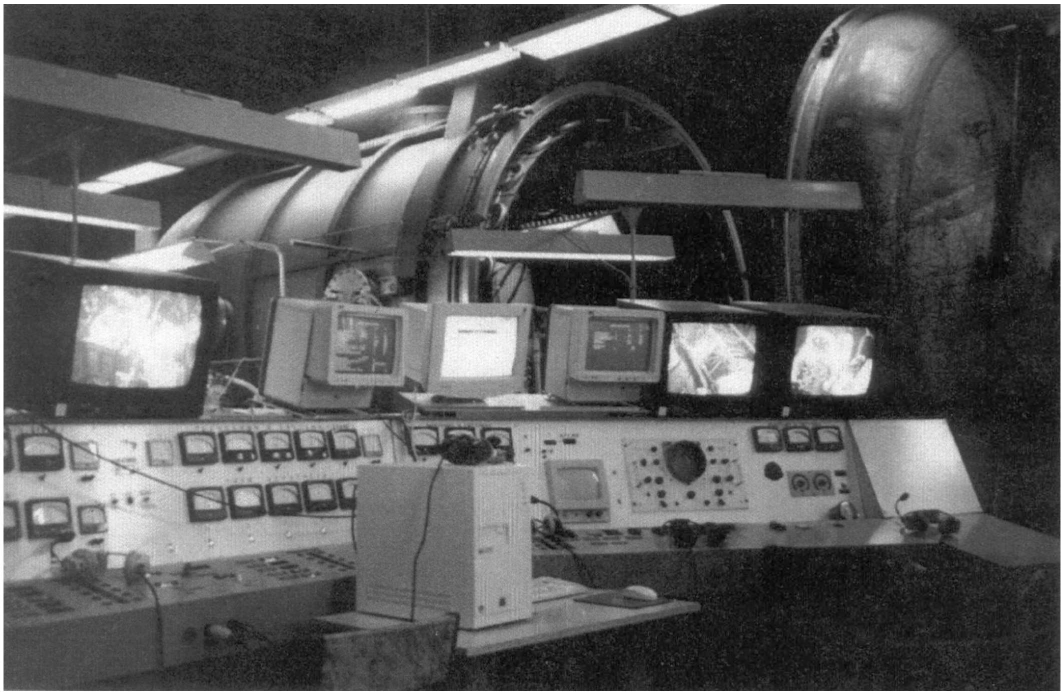


Figure 1. Space simulation chamber.

Table 1. Operator training samples.

Sample No.	Material	Joint Thickness and Type	Operator	Processing Date
1–5–D–4	304 SS	0.060-in lap	Avdeev	29–Apr–98
1–6–E–10	Al 2219	0.080-in bead-on-plate	Avdeev	29–Apr–98
1–6–D–7	304 SS	0.032-in cut	Avdeev	29–Apr–98
2–6–B–6	Al 5456	0.080-in lap	Padalko	7–May–98
1–5–D–1	304 SS	0.060-in lap	Padalko	7–May–98
1–6–E–11	Al 1100	0.080-in bead-on-plate	Padalko	7–May–98
2–6–B–3	Al 5456	0.080-in butt	Avdeev	13–May–98
1–6–E–5A	Al 2219	0.080-in lap	Avdeev	13–May–98
1–6–D–5	Ti–6Al–4V	0.040-in cut	Avdeev	13–May–98
1–6–C–5	Al 5456	0.080-in debris impact	Avdeev	13–May–98
1–4–E–7A	Ti–6Al–4V	0.035-in tube plug	Avdeev	13–May–98
1–4–E–9	304 SS	Tube braze	Avdeev	13–May–98
1–4–C–2	304 SS	0.060-in butt	Padalko	19–May–98
1–4–D–2	Ti–6Al–4V	0.060-in lap	Padalko	19–May–98
1–4–C–7	Ti–6Al–4V	0.060-in butt	Avdeev	19–May–98
1–4–E–7B	Ti–6Al–4V	0.035-in tube plug	Padalko	19–May–98
1–6–C–6	Al 2219	0.080-in butt	Avdeev	21–May–98
1–6–E–5B	Al 2219	0.080-in lap	Avdeev	21–May–98
1–5–D–8	Al 5456	0.024-in cut	Avdeev	21–May–98
1–5–D–6	Al 2219	0.024-in cut	Avdeev	21–May–98
1–6–A–1	Al 2219	0.080-in debris impact	Kaleri	22–May–98

Table 2. Sample material compositions.

Element	Material (%)			
	304 SS	Al 2219	Al 5456	Ti–6Al–4V
Al	–	Remainder	Remainder	6
C	0.080	–	–	0.040
Cr	18 to 20	–	0.050 to 0.200	–
Cu	–	5.800 to 6.800	0.100	–
Fe	Remainder	0.300	0.400	0.130
H	–	–	–	0.006
Mg	–	0.020	4.700 to 5.500	–
Mn	2	0.200 to 0.400	0.500 to 1.000	–
N	–	–	–	0.015
Ni	8 to 10.500	–	–	–
O	–	–	–	0.180
P	0.0450	–	–	–
S	0.030	–	–	–
Si	1	0.200	0.250	–
Ti	–	0.020 to 0.100	0.200	Remainder
V	–	0.050 to 0.150	–	0.040
Zn	–	0.100	0.250	–
Zr	–	0.200 to 0.250	–	–
Other (maximum)	–	0.150	0.150	–

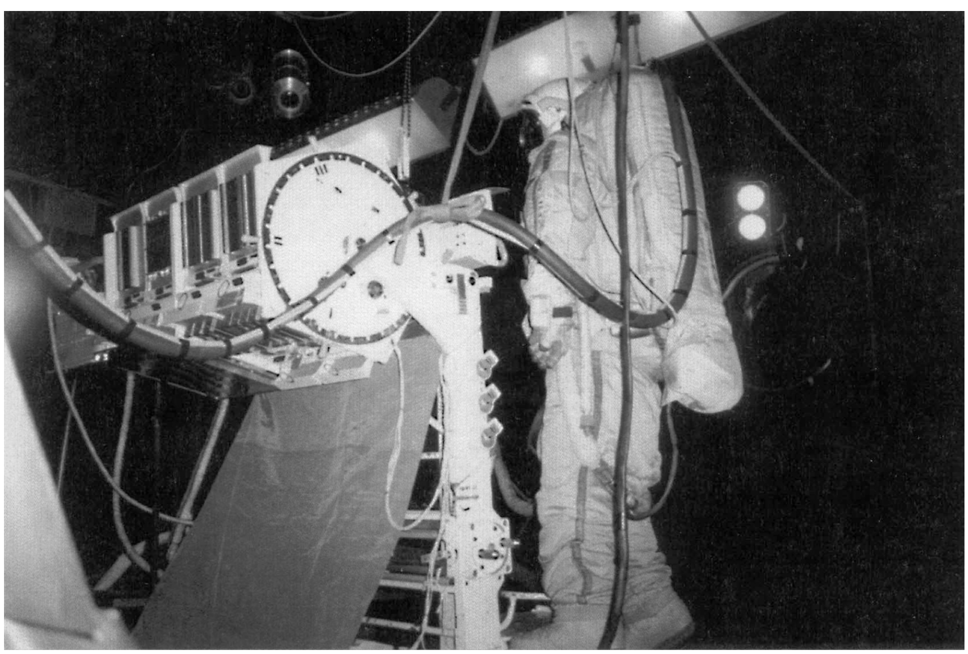


Figure 2. Orlan spacesuit with counterweight.

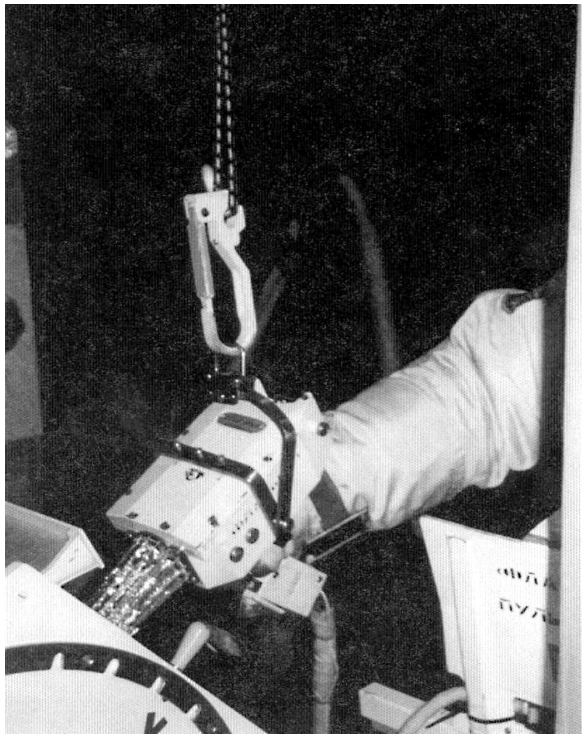


Figure 3. UHT with counterweight.

The samples were mounted on cassettes positioned on five faces of a drum. They were organized by level of difficulty to complete, with samples of similar configuration or material placed together. First, each operator processed the bead-on-plate samples to gain familiarity with the equipment and the process. Then, the operator executed lap joint fillet welds, cuts, and square butt joints. Finally, the operator welded a repair patch on the U.S. component, tube plug welds, and tube brazing. A standard UHT was used to complete each operation, except for the remaining Al 5456 samples, which were welded with a handtool outfitted with a filler wire mechanism. The latter tool was used to process lap joint fillet welds and square butt joints with a small gap, as well as to weld a repair patch on the Russian component.

The manned vacuum chamber runs were limited to a predetermined period. Some operators were able to process more samples than others, depending on operator fatigue and the types of samples being processed. Sample limitations did not allow all operators to process the same number or type of samples.

2. EVALUATION OF PLATE SAMPLES

2.1 Visual Examination

The general appearance of these welded samples indicated that the vacuum level was adequate for welding in the space simulation chamber. The chamber pressure was reported at 8×10^{-4} torr.[2] However, the pressure gauge may not have been located near the weld samples so the pressure there could have been different. The welds were primarily colored gold on 304 SS and shiny silver on Ti–6Al–4V, which is acceptable per industry standards. The Al welds had appearances that were more indicative of inadequate shielding from the atmosphere. The Al 5456 welds were very rough with a dull finish, and some samples had pores open to the surface. The Al 2219 welds were also a dull gray color, but had a smoother surface finish. Figures 4 and 5 show typical weld appearances for each of the four materials.

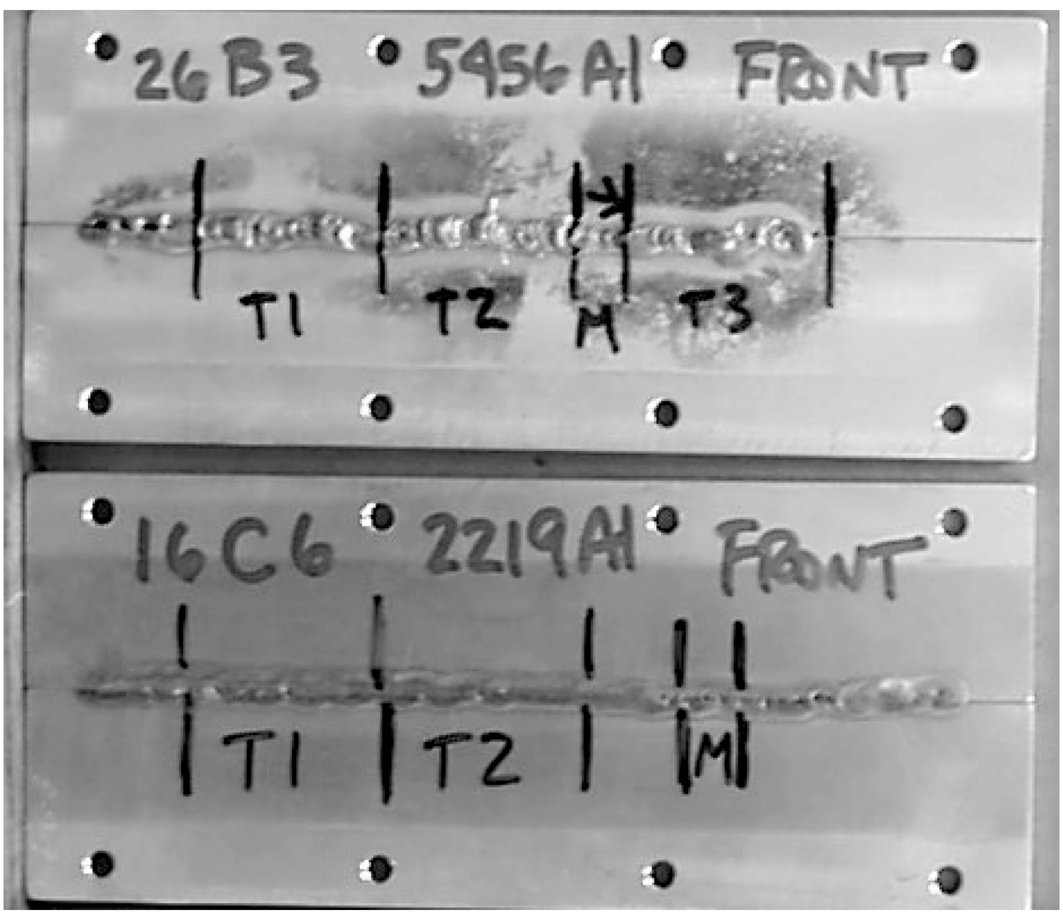


Figure 4. Al 5456 and 2219 welds.

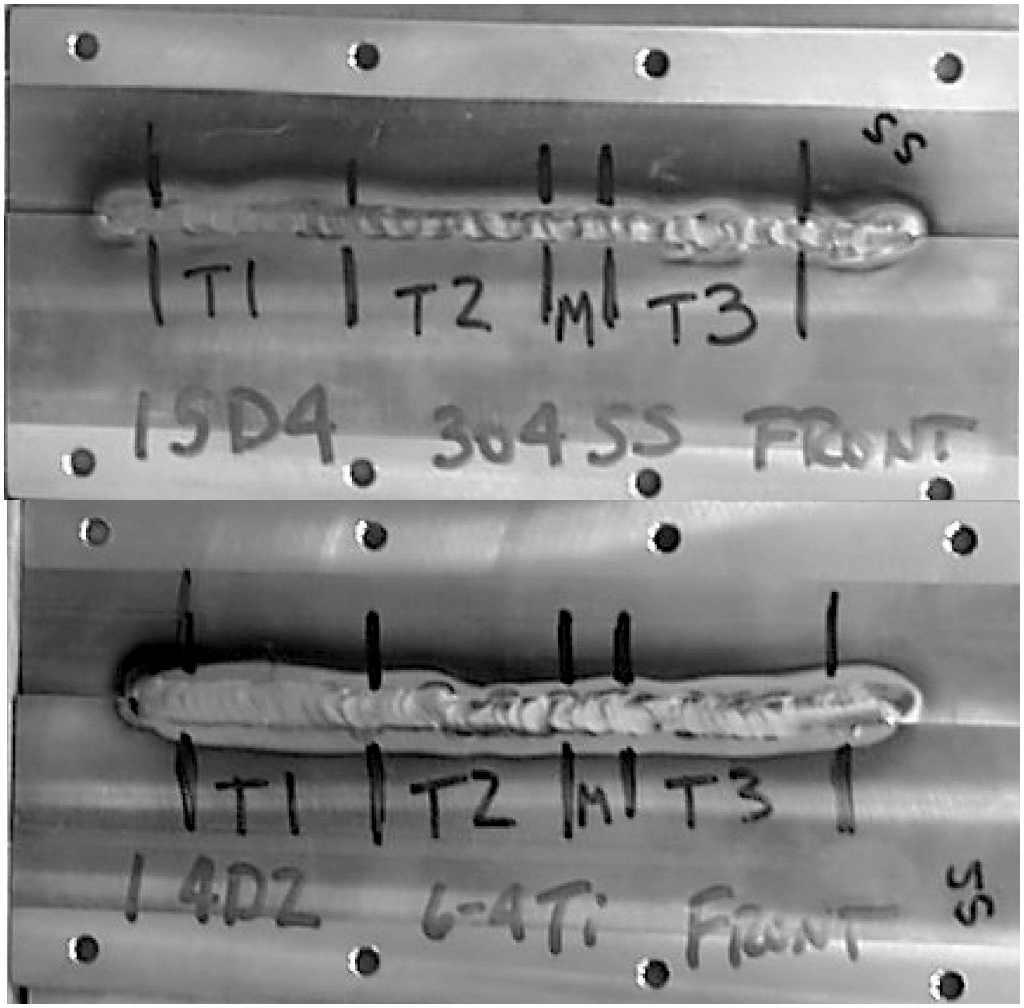


Figure 5. 304 SS and Ti–6Al–4V welds.

First, the operators processed bead-on-plate samples of either Al 2219 or 1100. These samples provided them with an opportunity to become familiar with the operation of the UHT and to concentrate only on the molten pool dynamics, without the distraction of trying to follow a weld seam at the same time. The bead-on-plate welds were also intended to provide metallurgical comparisons between an alloyed weld solidification to a pure alloy weld solidification for samples processed in space. The Al 2219 bead-on-plate sample fully penetrated the plate with a consistent weld width, whereas the Al 1100 bead-on-plate sample had partial penetration, as well as a consistent, although very narrow, width (fig. 6).

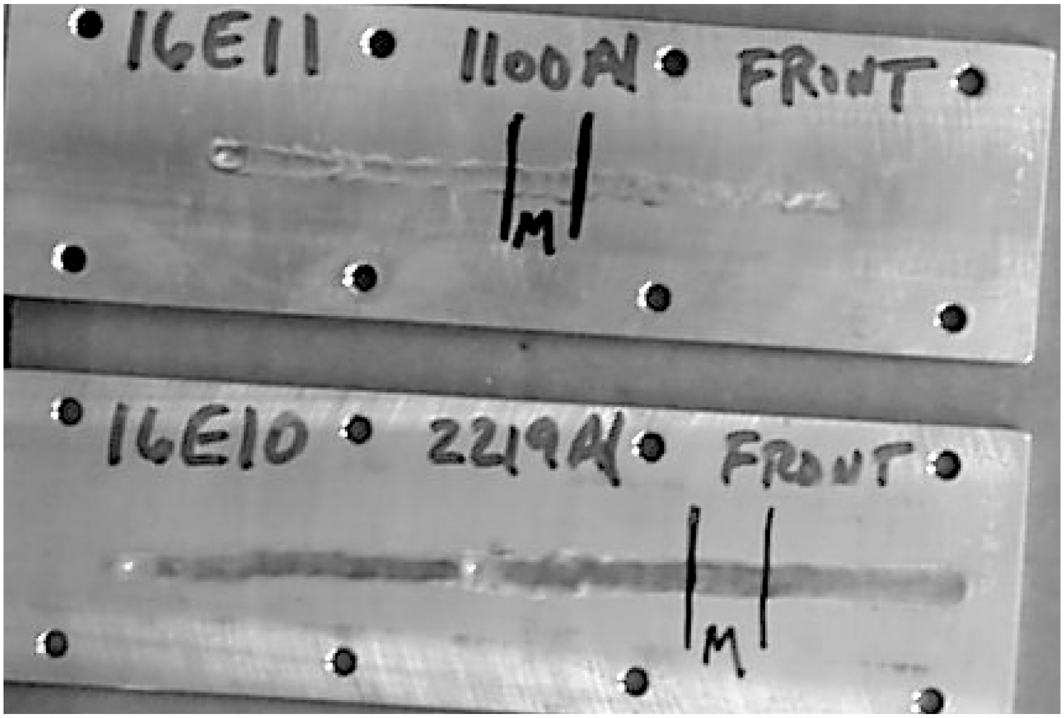


Figure 6. Al 1100 and 2219 bead-on-plate welds.

Ten plate samples were received that were either butt or lap joints. Only one of these samples, a butt joint on Ti–6Al–4V, was welded where the operator missed the joint (fig. 7). This joint may have been missed due to insufficient ambient lighting or the extreme brightness of a Ti–6Al–4V molten weld pool. Unfortunately, this sample was also the only butt joint sample that was full penetration the whole length. Partial penetration was seen on the other butt joint samples, one of each material. The operators maintained consistent weld widths on the butt joints, implying a steady travel speed, even on Al 5456 welded with filler wire.

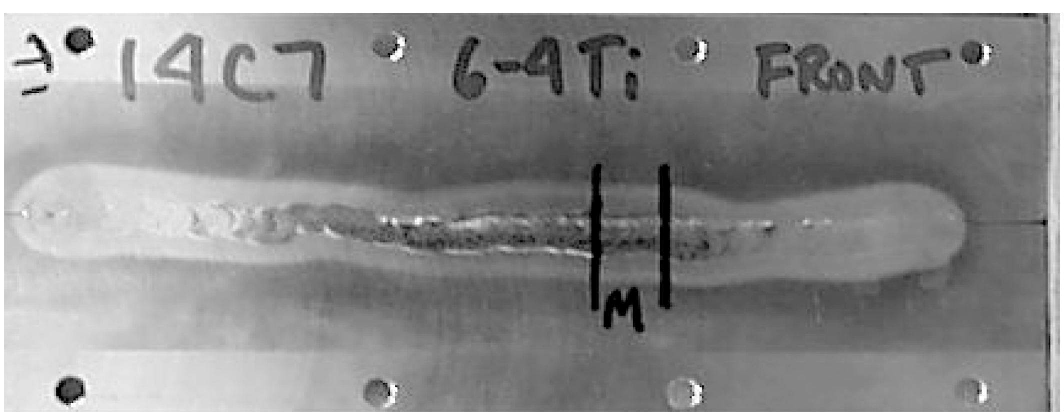


Figure 7. Ti–6Al–4V butt joint (sample 1–4–C–7).

The other six plate samples were processed with lap joint fillet welds, which also had a consistent weld width. Figure 8 shows that the fillets fully penetrated through the bottom plate of Al 2219. Figure 9 shows that only the Al 5456, again welded with filler wire, did not consume the weld joint. Figures 10 and 11 show fillet welds on Ti–6Al–4V and 304 SS, respectively. All fillet welds were visually acceptable, with a consistent weld width and seam tracking, except for the Al 5456 sample. The lap joint configuration may be easier to weld in plate samples.

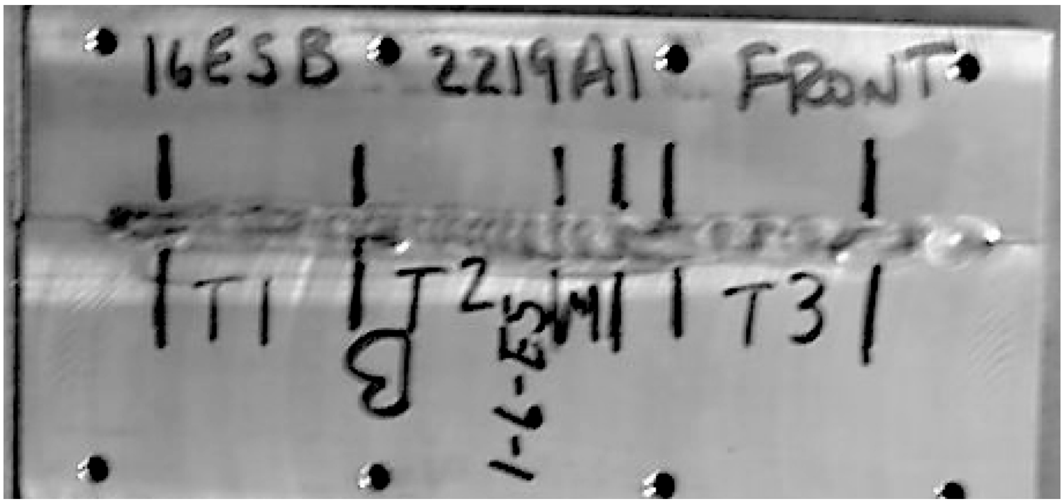


Figure 8. Al 2219 fillet weld (sample 1–6–E–5B).

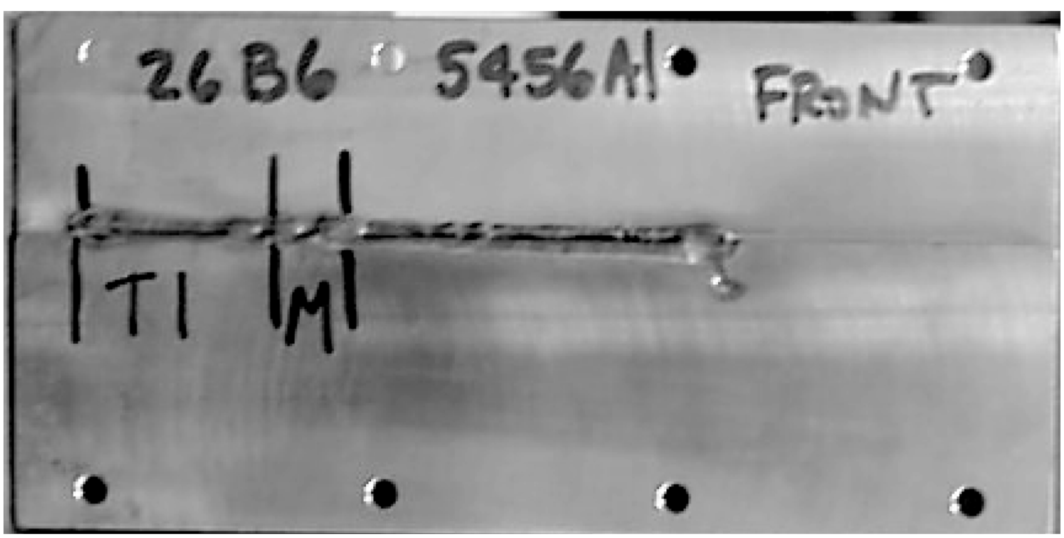


Figure 9. Al 5456 fillet weld (sample 2–6–B–6).

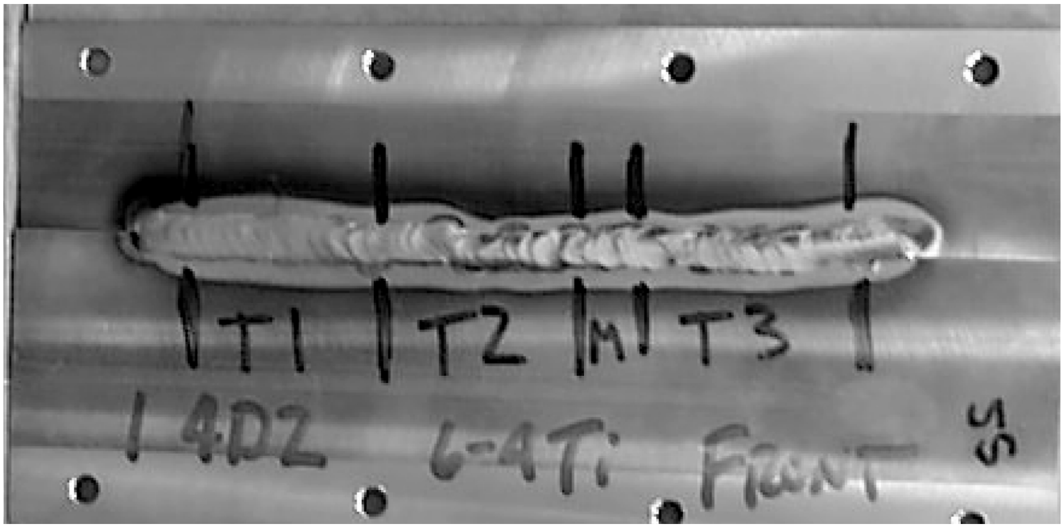


Figure 10. Ti–6Al–4V fillet weld (sample 1–4–D–2).

Figure 11. 304 SS fillet weld (sample 1–5–D–1).

The final plate samples were used to demonstrate cutting with the UHT. The operators cut four plates, one of each material. The visual appearance showed consistent widths for the Al 2219 and 5456 cuts in 0.024-in-thick plate, with even melting evident along both edges of the cut (fig. 12). A different appearance was presented by the 304 SS and Ti–6Al–4V cuts in 0.032-in-thick plate (fig. 13) These widths were very inconsistent, with uneven melting evident along the cut edges. In fact, the large solidified blobs could represent a safety concern if they were to release from the plate while molten. The 304 SS cut sample also showed evidence of spatter on the backside of the plate, indicating that molten metal was released during the cutting operation (fig. 14).

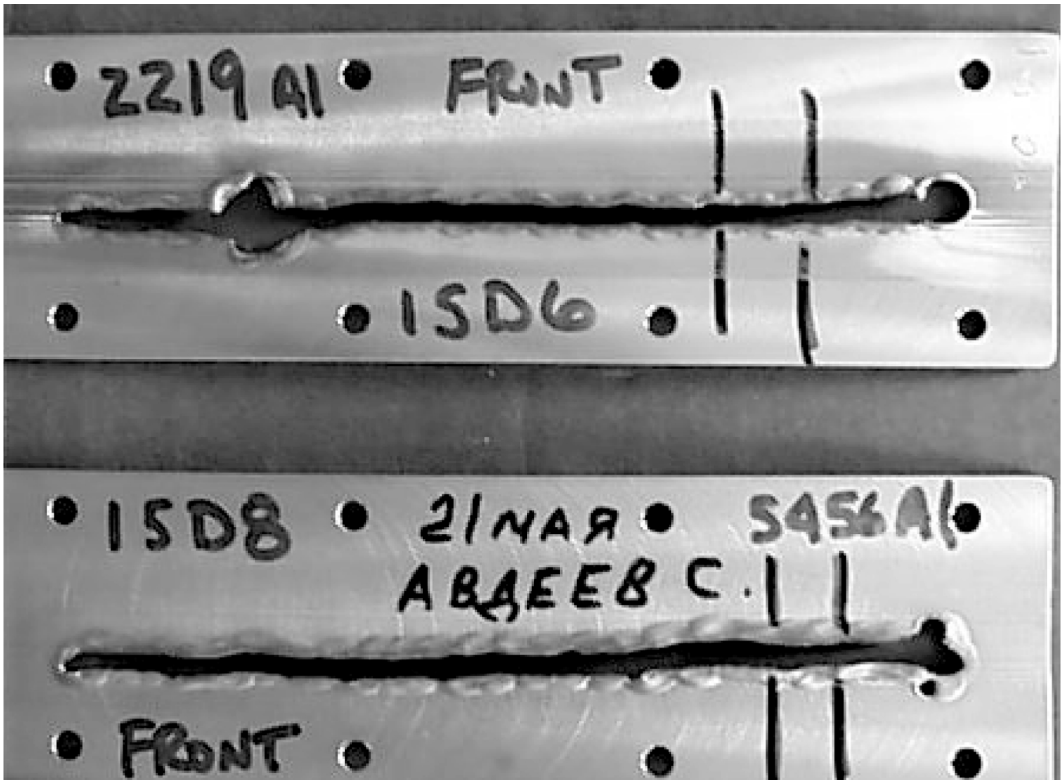


Figure 12. Al 2219 and 5456 cutting samples.

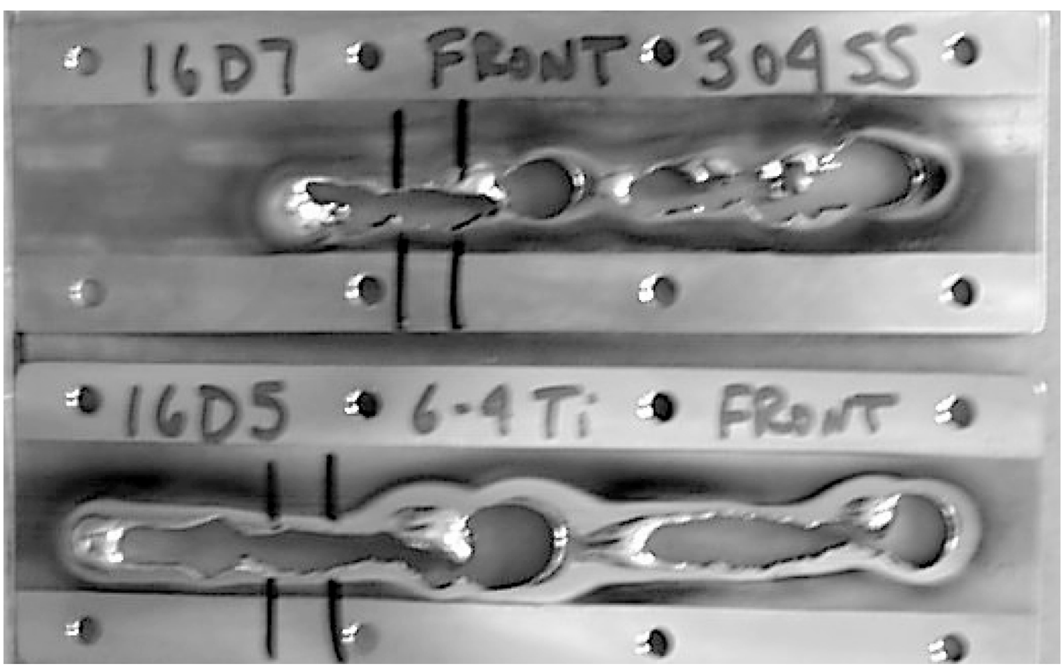


Figure 13. 304 SS and Ti–6Al–4V cutting samples.

Figure 14. 304 SS cutting sample with spatter on back.

2.2 Nondestructive Inspection

Radiography was used for nondestructive inspection of 10 plate samples in either the butt or lap joint configurations, as well as the two bead-on-plate samples (table 3). No porosity was seen in the SS welds, and only the Ti–6Al–4V weld sample, which missed the joint, had intermittent porosity. All samples of Al 2219 and 5456 contained some level of porosity, except for the bead-on-plate samples. Both butt joints had excessive porosity the whole length, while the lap joint fillet welds had scattered porosity. These results may have been caused by contaminated weld joint interfaces.

Table 3. Radiographic inspection results.

Sample	Description	Material	X Ray
1–6–E–11	Bead-on-plate weld	Al 1100	No defects
1–6–E–10	Bead-on-plate weld	Al 2219	No defects
1–6–C–6	Butt joint	Al 2219	Porosity whole length, intermittent lack of penetration
1–6–E–5A	Fillet weld	Al 2219	Few pores
1–6–E–5B	Fillet weld	Al 2219	One pore
1–4–C–2	Butt joint	304 SS	Lack of penetration
1–5–D–4	Fillet weld	304 SS	No defects
1–5–D–1	Fillet weld	304 SS	No defects
2–6–B–3	Butt joint, 0.02 in	Al 5456	Porosity whole length, lack of penetration
2–6–B–6	Fillet weld	Al 5456	Few pores, lack of fusion
1–4–C–7	Butt joint	Ti–6Al–4V	Intermittent porosity, missed joint
1–4–D–2	Fillet weld	Ti–6Al–4V	No defects

2.3 Metallurgical Evaluation

Metallographic examination was conducted on samples removed from the welded plates, bead-on-plate, and cut plates of all alloys studied. Weld quality was determined by observing the penetration depth, defects, weld geometry, and microstructure. In addition, microhardness traverses were made.

Figures 15–18 show metallurgical cross sections for the 304 SS samples, which consisted of one butt joint square groove weld, two lap joint fillet welds, and one cut plate. The fillet welds had good depth of penetration. One appeared to completely penetrate the bottom plate, while the second penetrated half the thickness of the bottom plate. Figure 19 shows a lack-of-penetration defect that was present in the square groove weld, which appeared to be off the centerline of the joint and did not completely penetrate. No observations were made of defects such as porosity or cracking.

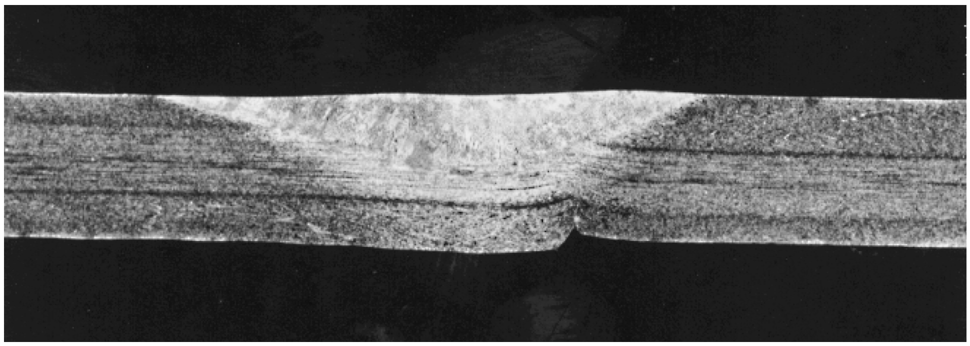


Figure 15. 304 SS square butt weld (sample 1–4–C–2), × 10.

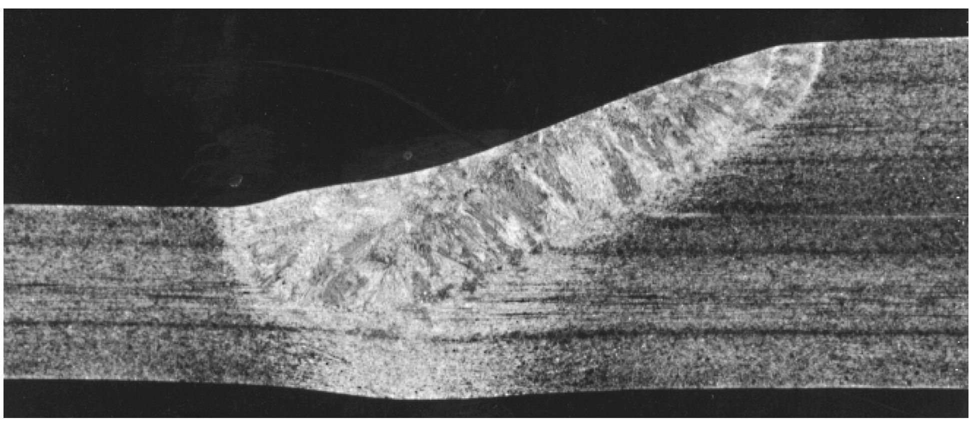


Figure 16. 304 SS lap/fillet joint (sample 1–5–D–4), × 12.

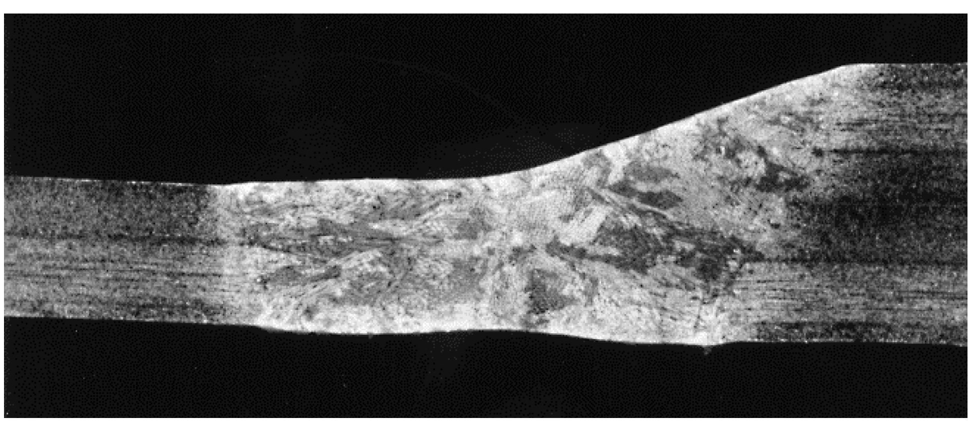


Figure 17. 304 SS lap/fillet joint (sample 1–5–D–1), × 10.

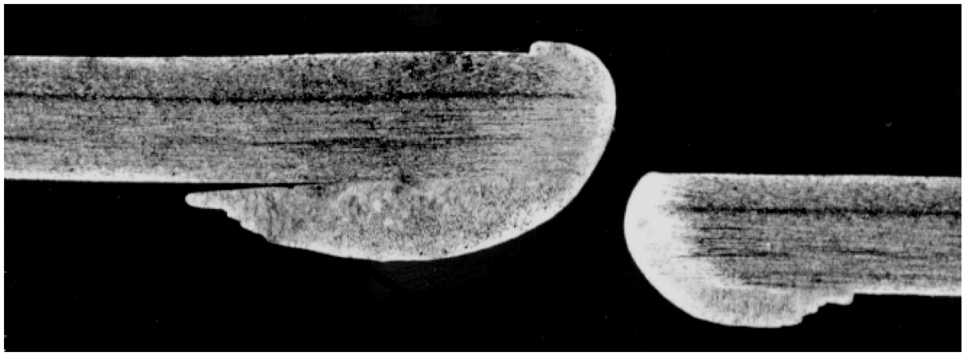


Figure 18. 304 SS cut plate (sample 1–6–D–7), × 12.5.

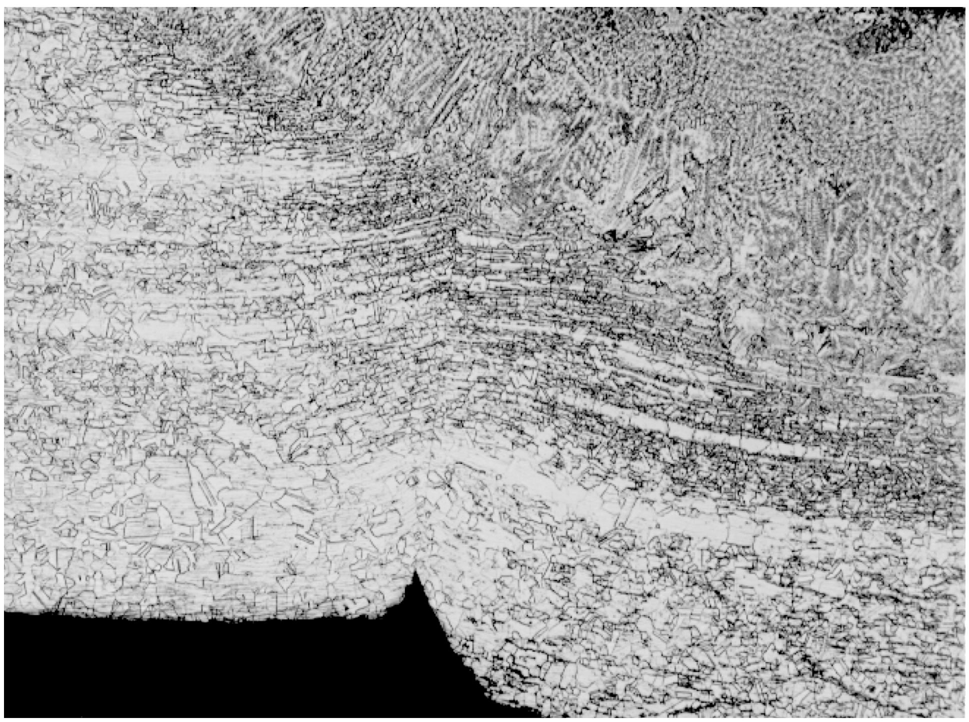


Figure 19. 304 SS square butt weld with lack of penetration (sample 1–4–C–2), × 50.

The welds were wide and flat, with short transitions from the weld metal to the base metal. The weld bead microstructure was dendritic, while the base metal structure was a fine-grained austenite. No apparent grain growth was observed.

The cut plate for the 304 SS sample did not exhibit the well-formed bead of molten metal seen in some of the other alloys. Instead, the molten material appeared to flow along the plate surface.

Figures 20–22 show micrographs of Ti–6Al–4V samples, including the butt joint square groove weld, lap joint fillet weld, and cut plate. The weld penetration depth was good on these samples, although the square groove weld was off center. No porosity or cracks were observed, although a minor notch or suck-back was seen in the square groove weld.

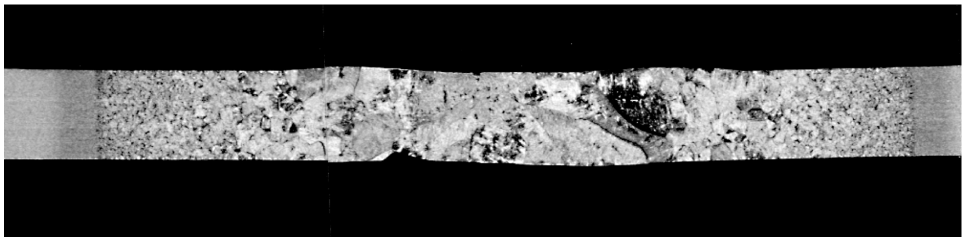


Figure 20. Ti–6Al–4V square groove butt weld (sample 1–4–C–7), × 10.

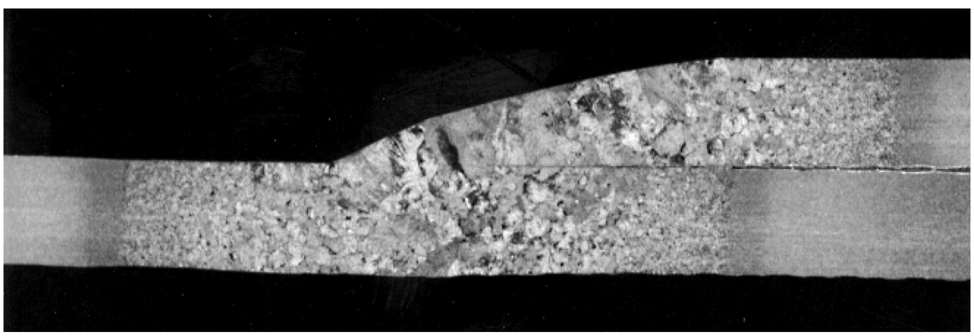


Figure 21. Ti–6Al–4V lap/fillet joint (sample 1–4–D–2), × 8.

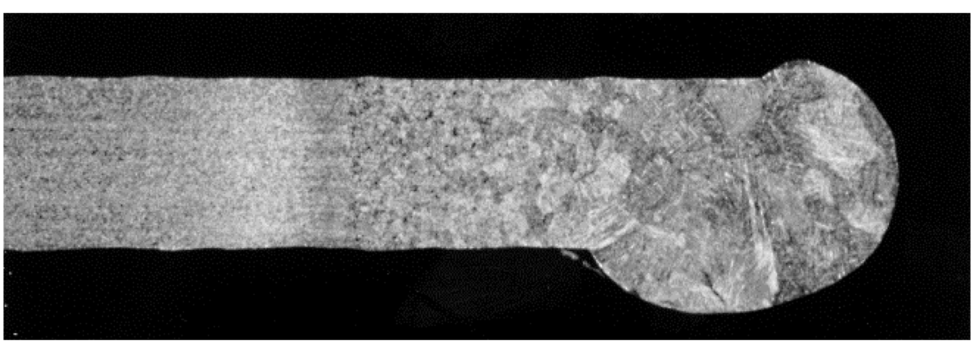


Figure 22. Ti–6Al–4V cut plate (sample 1–6–D–5), × 20.

These welds were wide, with very large heat-affected zones. The base metal consisted of a mixture of fine α grains and β with acicular α. The weld bead consisted of very large grains of serrated α and transformed β with acicular α with a gradual transition to smaller grains in the heat-affected zone to the base metal structure.

The Ti–6Al–4V cut plate sample contained a bead of melted metal, with slight flow along the plate. The heat-affected zone was large for this sample.

Figures 23–27 show cross sections of Al 2219, including one butt joint, two lap joints, one bead-on-plate, and one cut plate. All welds and bead-on-plate showed good penetration. However, figure 23 shows that the butt joint had a crater or lack of fill in the weld crown, while the lap joints both exhibited porosity, with one lap weld containing a crack (fig. 28) as well.

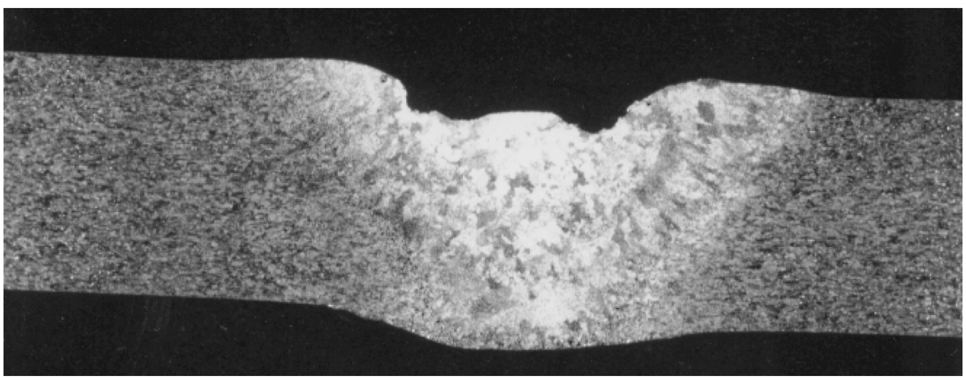


Figure 23. Al 2219 square groove weld (sample 1–6–C–6), × 12.5.

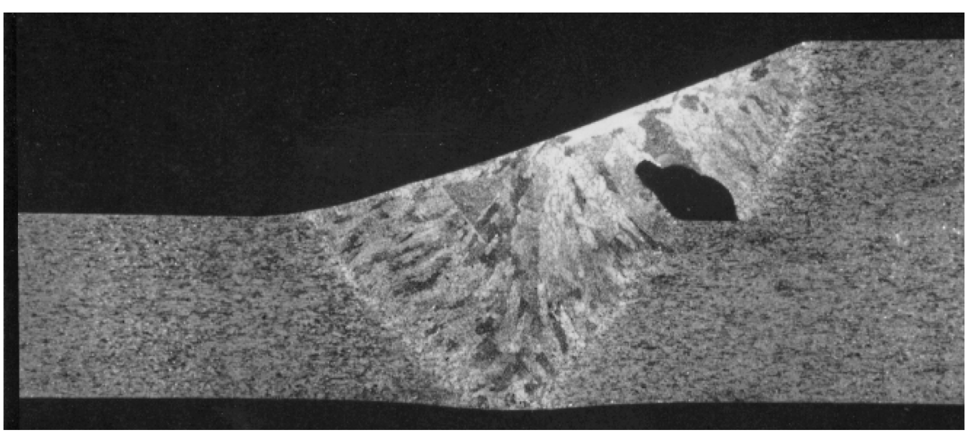


Figure 24. Al 2219 lap/fillet joint (sample 1–6–E–5A), × 10.

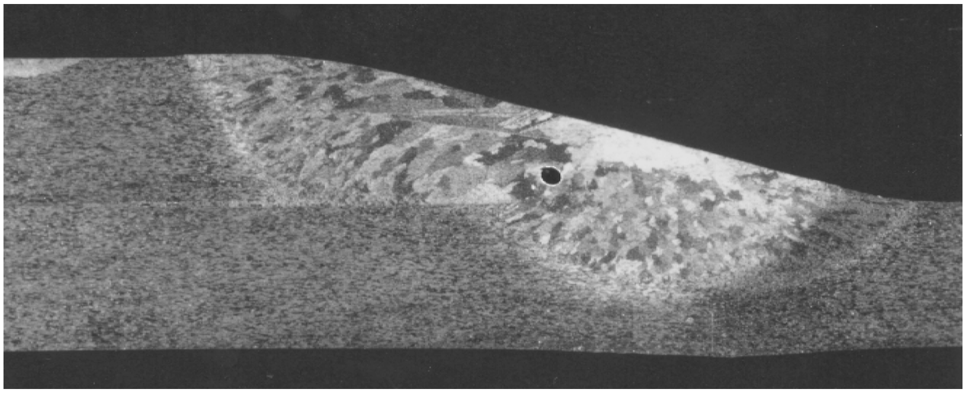


Figure 25. Al 2219 lap/fillet joint (sample 1–6–E–5B), × 10.

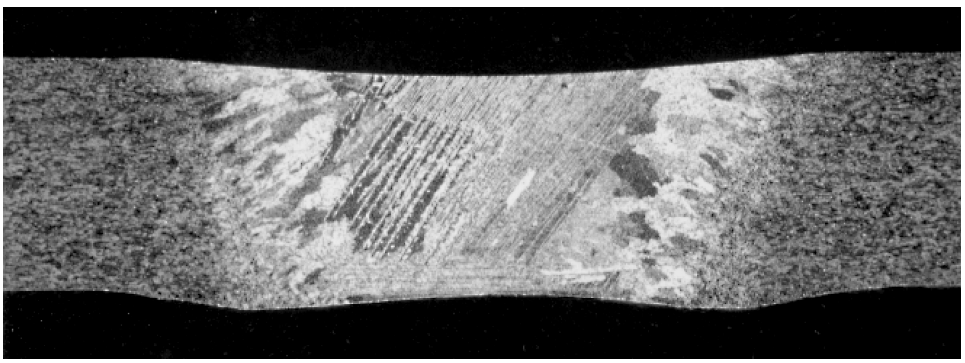


Figure 26. Al 2219 bead-on-plate weld (sample 1–6–E–10), × 12.5.

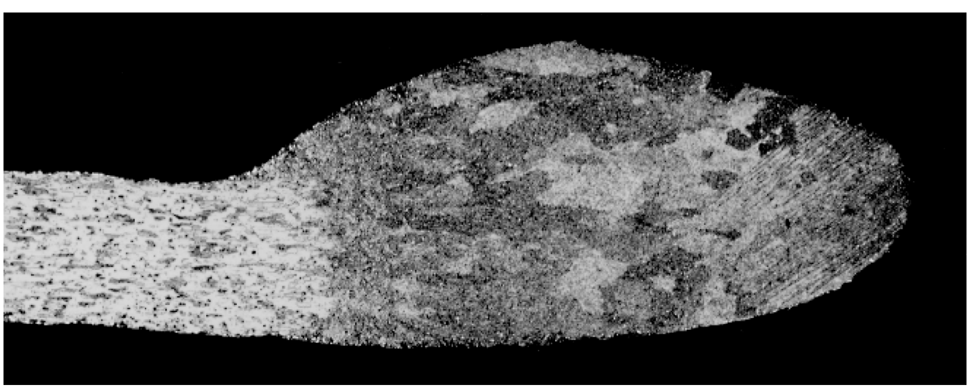


Figure 27. Al 2219 cut plate (sample 1–5–D–6), × 25.

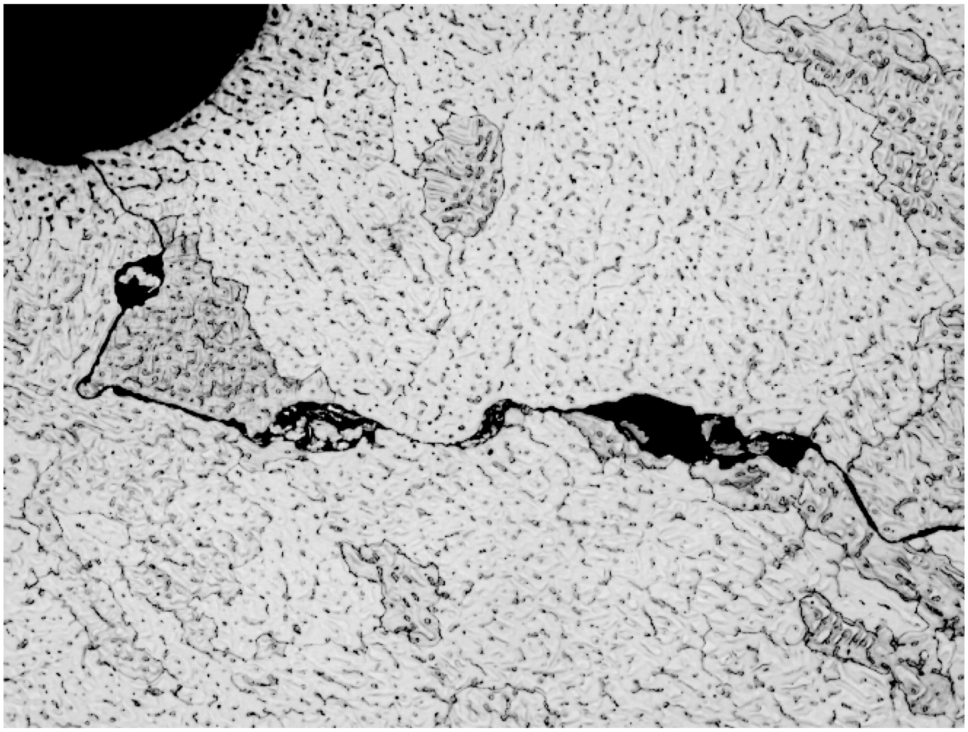


Figure 28. Al 2219 weld with cracking (sample 1–6–E–5B), × 200.

The welds were wide, with one lap weld showing a large heat-affected zone on the top plate. The weld bead had a dendritic microstructure. The heat-affected zone had a zone of equiaxed grains along the fusion line, which had a tendency for microporosity, as well as segregation of $CuAl_2$ along the grain boundaries. The base metal microstructure consisted of grains of solid solution Al, with particles of $CuAl_2$ and $(Fe,Mn)_3SiAl_{12}$.

The cut plate of the Al 2219 sample had a large melted bead, with little evidence of molten metal flowing along the plate. The heat-affected zone did not appear to be large.

Figures 29–31 show cross sections of Al 5456, including one square groove butt joint, one lap joint fillet weld, and one cut plate. The lap joint fillet weld showed good penetration, although the square groove weld was slightly off-center and not fully penetrated. Some porosity was seen as well. Figure 32 shows that the lap joint fillet weld also had porosity, with some cracking.

The welds were wide and flat, with very short heat-affected zones. The weld bead had a dendritic structure. The base metal microstructure consisted of large MgSi particles and finer precipitates of $(Fe,Mn)Al_6$ and Mg_2Al_3. The Al 5456 cut plate had a well-formed bead of molten metal, with a small heat-affected zone.

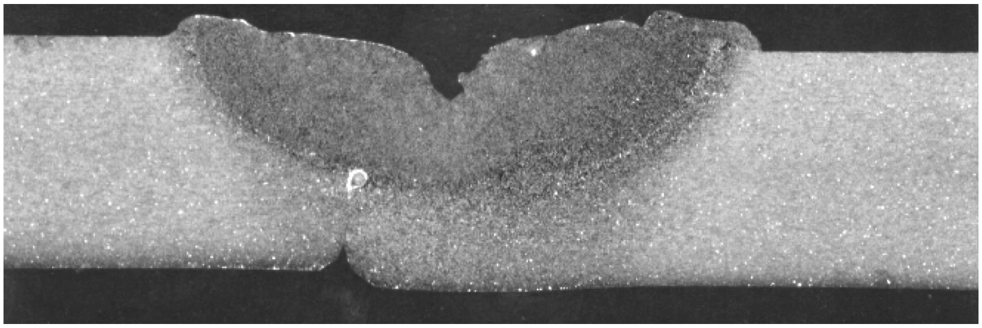


Figure 29. Al 5456 square groove weld (sample 2–6–B–3), × 12.5.

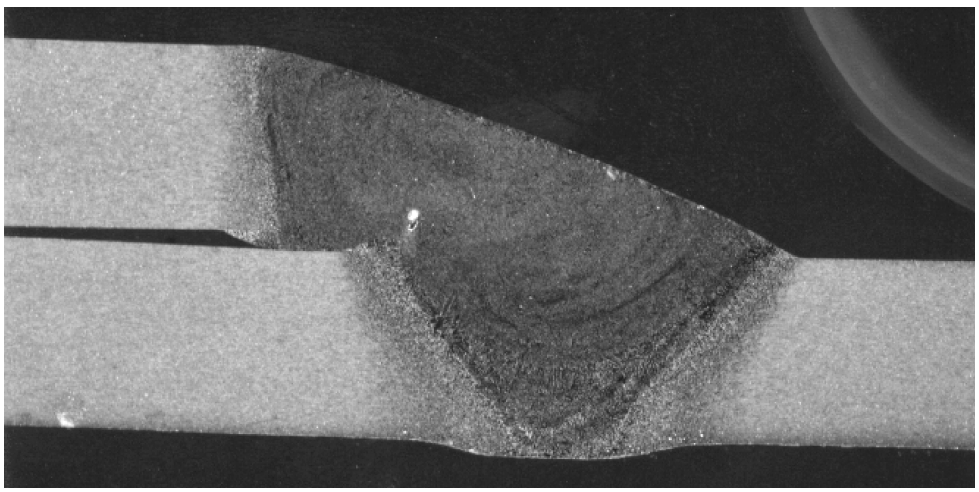


Figure 30. Al 5456 lap/fillet joint (sample 2–6–B–6), × 10.

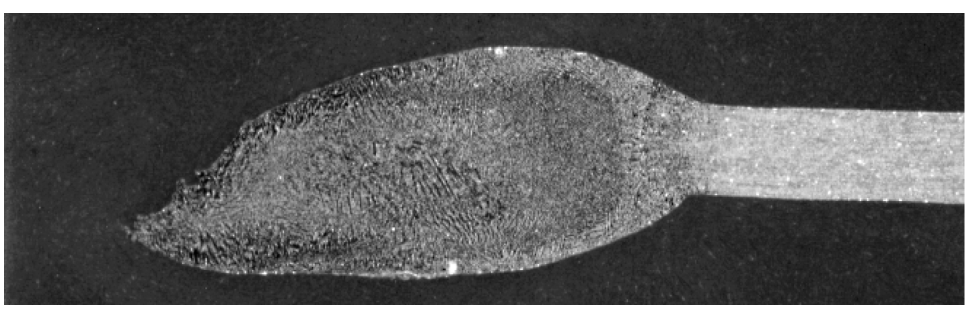


Figure 31. Al 5456 cut plate (sample 1–5–D–8), × 15.

Figure 32. Al 5456 fillet weld with porosity or cold fold (sample 2–6–B–6), × 50.

Figure 33 shows the cross section of a bead-on-plate sample of Al 1100. The penetration was less than half the plate thickness, with a relatively wide heat-affected zone.

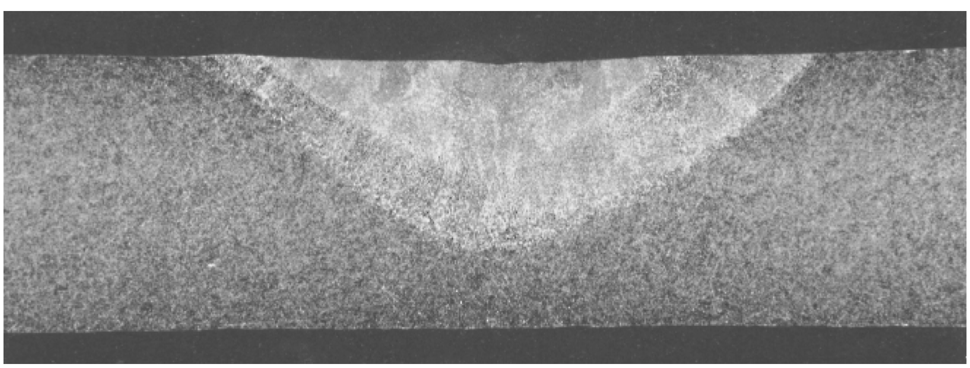


Figure 33. Al 1100 bead-on-plate weld (sample 1–6–E–11), × 12.5.

Figures 34–37 show diagrams of typical hardness traverses for the various alloys. Generally, few hardness variations were seen in the welds made on 304 SS and Ti–6Al–4V, while Al 2219 and 5456 had softer weld beads and heat-affected zones than the parent material.

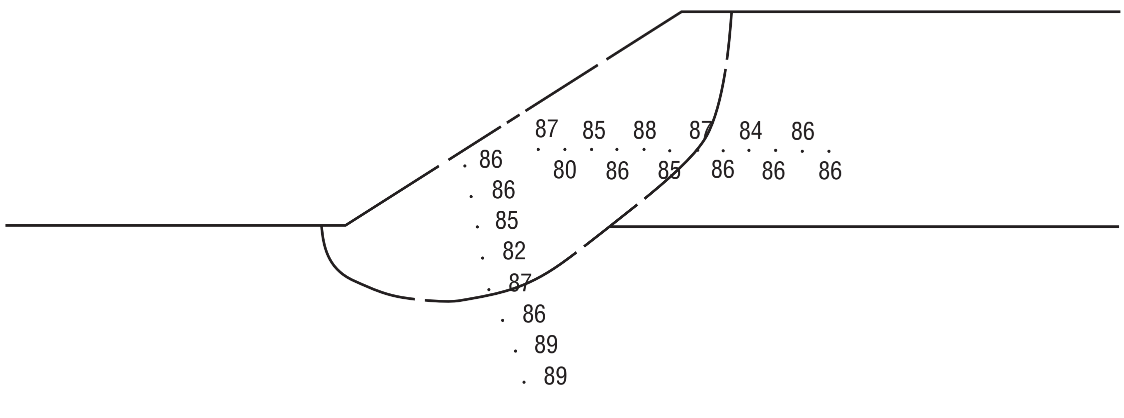


Figure 34. Hardness traverse (Rockwell B) in 304 SS lap/fillet joint (sample 1–5–D–4).

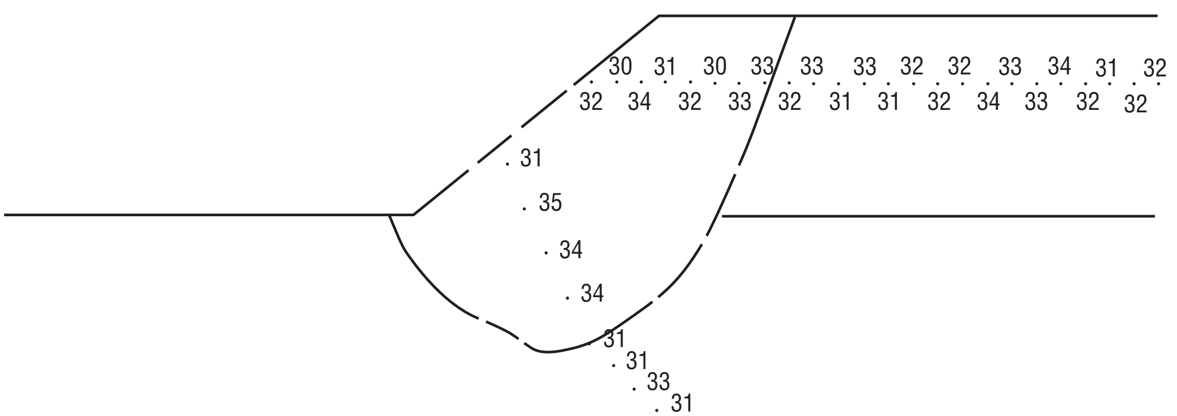


Figure 35. Hardness traverse (Rockwell C) in Ti–6Al–4V lap/fillet joint (sample 1–4–D–2).

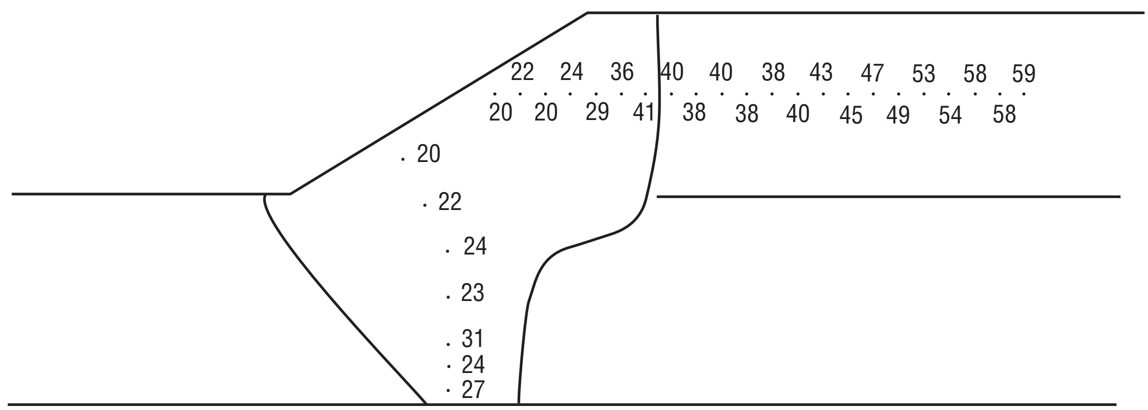


Figure 36. Hardness traverse (Rockwell B) in Al 2219 lap/fillet joint (sample 1–6–E–5A).

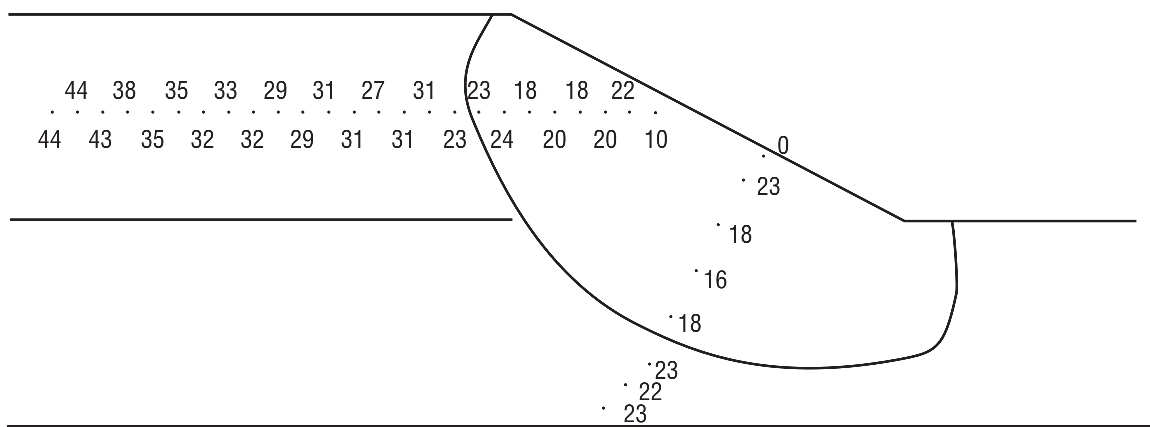


Figure 37. Hardness traverse (Rockwell B) in Al 5456 lap/fillet joint (sample 2–6–B–6).

2.4 Mechanical Properties

Samples for mechanical testing were sectioned from selected areas of welds with known defects (fig. 38). Tests were conducted on 8 samples from butt joints and 16 samples from fillet joints, as well as material from each alloy. Mechanical tension testing was conducted at ambient temperature, in accordance with the American Society for Testing and Materials E8 procedures, using a MTS Systems Corporation servohydraulic load frame, with an Instron® digital controller. Samples were pulled to failure using hydraulic friction grips (table 4).

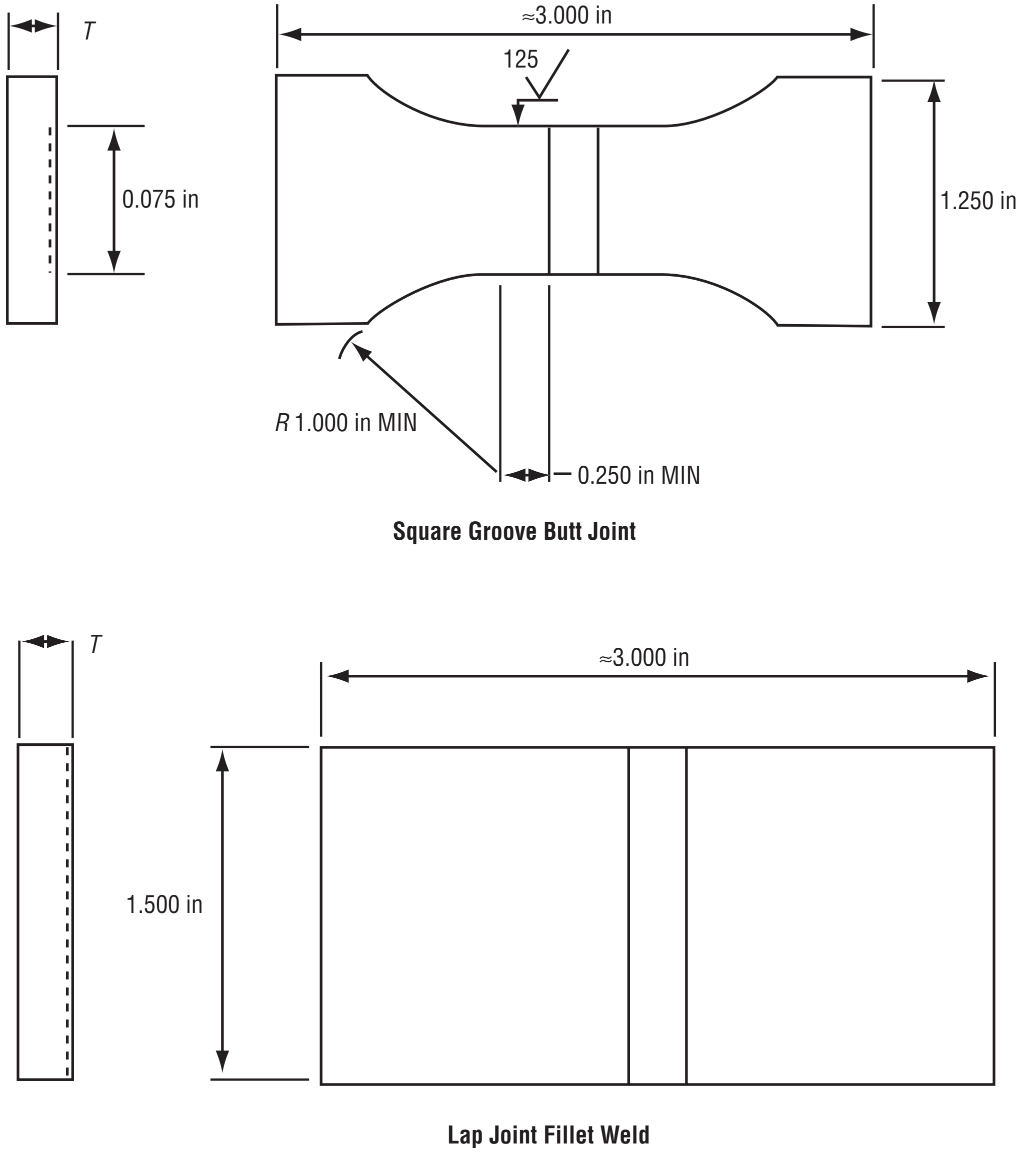


Figure 38. Sample configuration for mechanical testing.

Table 4. Tensile test results.

Sample No.	Parent Metal Averages (in)		Joint Design	Material Type	Load (lb)	UTS		Failure Location	Operator	Processing Date
	Width	Thickness				ksi	MPa			
14C2–T1	0.7390	0.0560	Butt	304 SS	3,851	93.06	640.22	Fusion zone	Padalko	19–May–98
14C2–T2	0.7500	0.0545	Butt	304 SS	4,478	109.55	753.73	Fusion zone	Padalko	19–May–98
14C2–T3	0.7400	0.0550	Butt	304 SS	3,368	82.75	569.33	Fusion zone	Padalko	19–May–98
14D2–T1	1.2290	0.0530	Lap/fillet	Ti–6Al–4V	6,915	106.16	730.39	Fusion zone at edge of lap	Padalko	19–May–98
14D2–T2	1.2260	0.0520	Lap/fillet	Ti–6Al–4V	6,185	97.02	667.47	Fusion zone at edge of lap	Padalko	19–May–98
14D2–T3	1.2230	0.0500	Lap/fillet	Ti–6Al–4V	5,970	97.63	671.69	Fusion zone at edge of lap	Padalko	19–May–98
15D1–T1	1.2480	0.0550	Lap/fillet	304 SS	7,048	102.68	706.44	Edge of bead	Padalko	7–May–98
15D1–T2	1.2440	0.0540	Lap/fillet	304 SS	7,318	108.94	749.49	Edge of bead	Padalko	7–May–98
15D1–T3	1.2430	0.0530	Lap/fillet	304 SS	7,216	109.53	753.59	Edge of bead	Padalko	7–May–98
15D4–T1	1.2310	0.0550	Lap/fillet	304 SS	5,575	82.34	566.52	Fusion zone at edge of lap	Avdeev	29–Apr–98
15D4–T2	1.2250	0.0530	Lap/fillet	304 SS	5,139	79.15	544.57	Fusion zone at edge of lap	Avdeev	29–Apr–98
15D4–T3	1.2010	0.0560	Lap/fillet	304 SS	5,044	75.00	515.98	Fusion zone at edge of lap	Avdeev	29–Apr–98
16C6–T1	0.7380	0.0750	Butt	Al 2219	1,937	35.00	240.77	Fusion zone	Avdeev	21–May–98
16C6–T2	0.7390	0.0790	Butt	Al 2219	2,076	35.56	244.65	Fusion zone	Avdeev	21–May–98
16E5A–T1	1.2410	0.0710	Lap/fillet	Al 2219	1,278	14.50	99.79	Fusion zone at edge of lap	Avdeev	13–May–98
16E5A–T2	1.2300	0.0735	Lap/fillet	Al 2219	1,353	14.97	102.97	Fusion zone at edge of lap	Avdeev	13–May–98
16E5A–T3	1.2260	0.0740	Lap/fillet	Al 2219	1,496	16.49	113.45	Fusion zone at edge of lap	Avdeev	13–May–98
16E5B–T1	1.2450	0.0730	Lap/fillet	Al 2219	1,518	16.70	114.91	Fusion zone at edge of lap	Avdeev	21–May–98
16E5B–T2	1.2500	0.0738	Lap/fillet	Al 2219	1,487	16.12	110.90	Fusion zone at edge of lap	Avdeev	21–May–98
16E5B–T3	1.2450	0.0730	Lap/fillet	Al 2219	1,714	18.86	129.75	Fusion zone at edge of lap	Avdeev	21–May–98
26B3–T1	0.7365	0.0745	Butt	Al 5456	2,513	45.80	315.10	Fusion zone	Avdeev	13–May–98
26B3–T2	0.7385	0.0755	Butt	Al 5456	1,765	31.66	217.79	Fusion zone	Avdeev	13–May–98
26B3–T3	0.7365	0.0745	Butt	Al 5456	1,275	23.24	159.87	Fusion zone/possible defect	Avdeev	13–May–98
26B6–T1	1.2240	0.0740	Lap/fillet	Al 5456	1,622	17.91	123.20	Fusion zone at edge of lap	Padalko	7–May–98

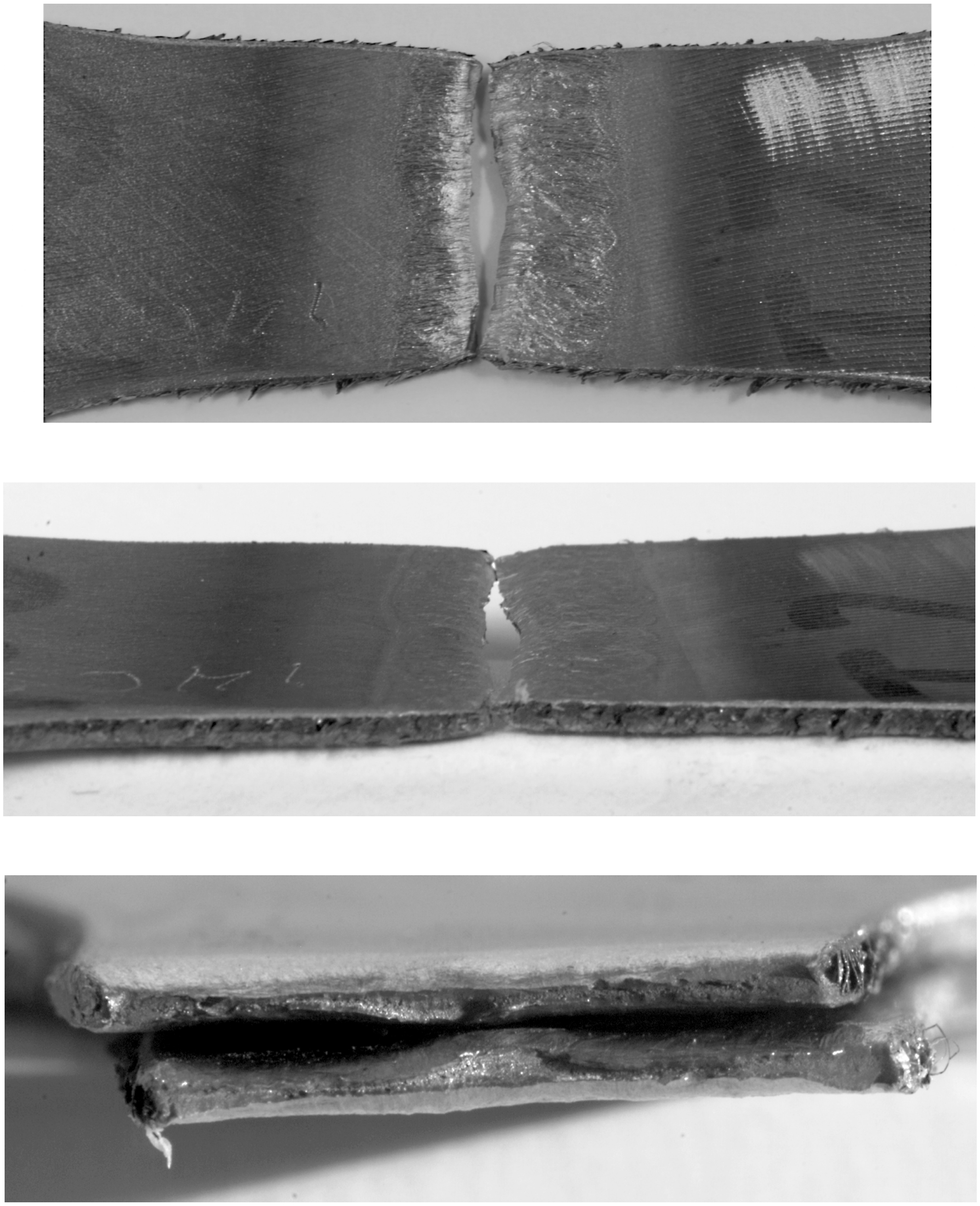
Table 5 presents a comparison between the average weld strengths for each data set and typical handbook values. Where typical values were not available for lap or fillet joints, 60 percent of the butt joint strength was used as the rule of thumb. Ultimate tensile strengths are shown as means plus or minus one standard deviation, where appropriate. All average weld strengths met or exceeded typical handbook values, except for the extremely defective welds on Al 5456.

Table 5. Typical weld strength comparison.

Joint Design	Material Type	Ultimate Tensile Strength (ksi)	Ultimate Tensile Strength (MPa)	Typical Weld Strength (ksi)	Typical Weld Strength (MPa)
Butt	304 SS	95.12±13.52	654.43±93.02	75[3]	515[3]
Lap/fillet	304 SS	92.94±15.81	639.43±108.80	45[4]	309[4]
Butt	Al 2219	35.28±0.40	242.71±2.74	35[5]	241[5]
Lap/fillet	Al 2219	16.27±1.53	111.96±10.56	16[5]	110[5]
Butt	Al 5456	33.56±11.40	230.92±78.44	46[5]	317[5]
Lap/fillet	Al 5456	17.91	123.2	17[5]	117[5]
Lap/fillet	Ti–6Al–4V	100.27±5.11	689.85±35.17	89[3]	618[3]

All butt joints failed in the fusion zone of the weld, and all fillet joints failed in the fusion zone of the weld at the edge of the lap joint. One butt joint, Al 5456, appeared to have defects on the fracture surface. Upon examination with an optical microscope, this sample was determined to have severe lack of fusion. When examined visually and with an optical microscope, the other samples were seen to contain lesser defects of porosity and lack of fusion in all other Al joints. The following observations indicate that the operators probably found Al to be inherently more difficult to weld than the other alloys.

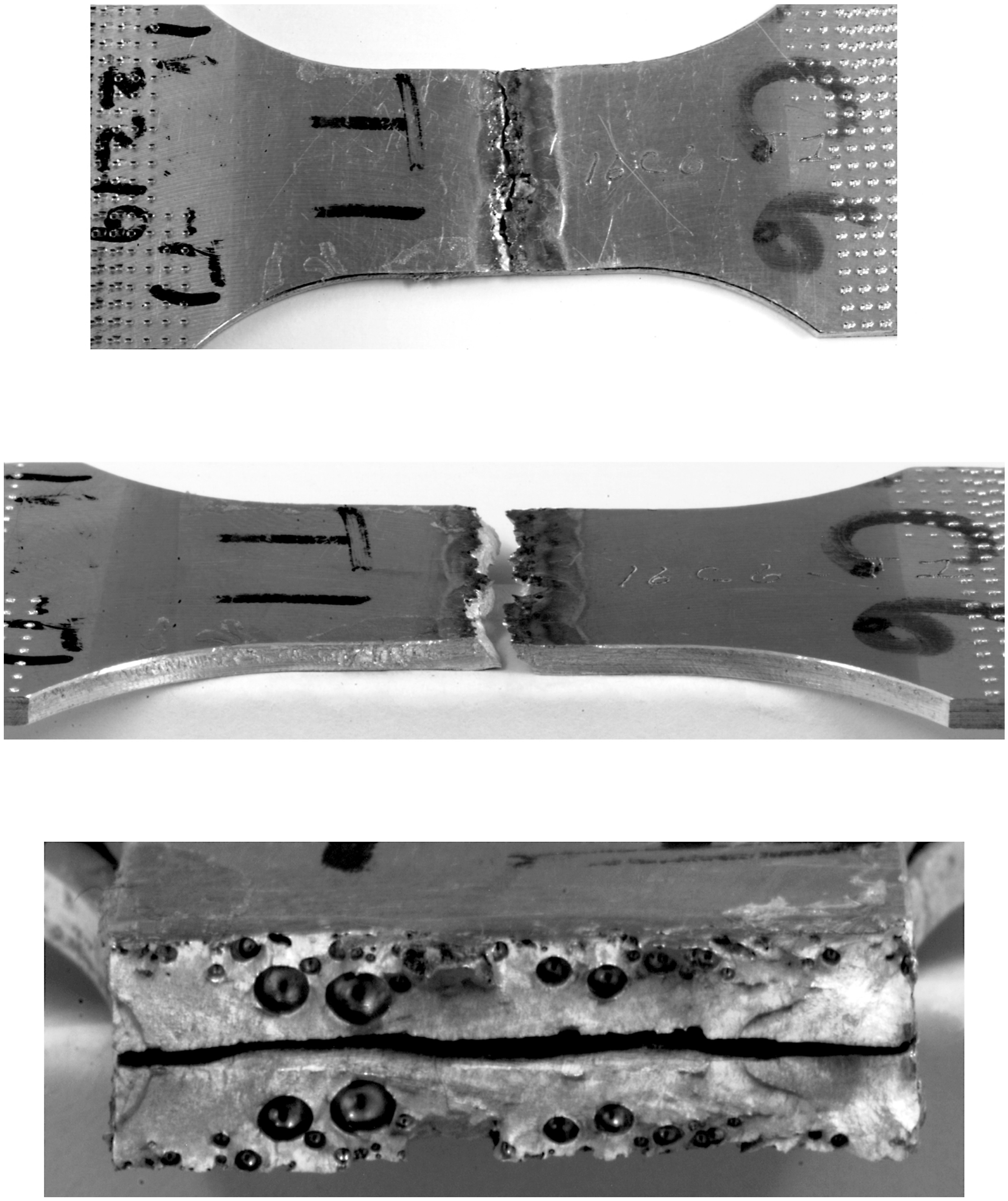
Figure 39 shows a butt weld joint on 304 SS. This fracture appeared clean with no obvious defects. Some ductility was apparent in both the fracture surface and poor fit of the broken pieces.



14C2–T2

Figure 39. 304 SS butt joint (test sample).

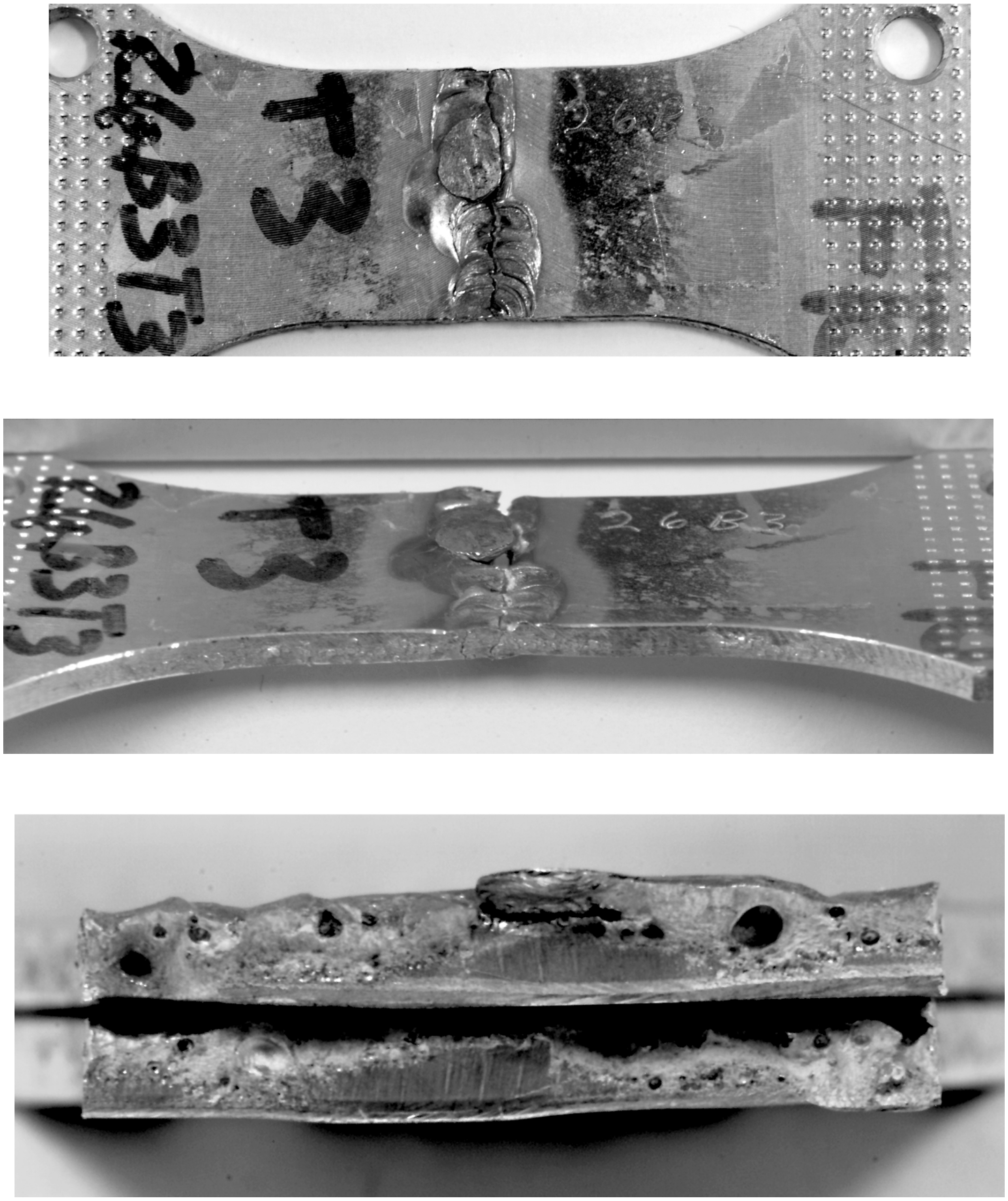
Figure 40 shows a butt weld joint on Al 2219. This fracture revealed many large pores and some lack of fusion with some good ductility on the fracture surface.



16C6–T1

Figure 40. Al 2219 butt joint (test sample).

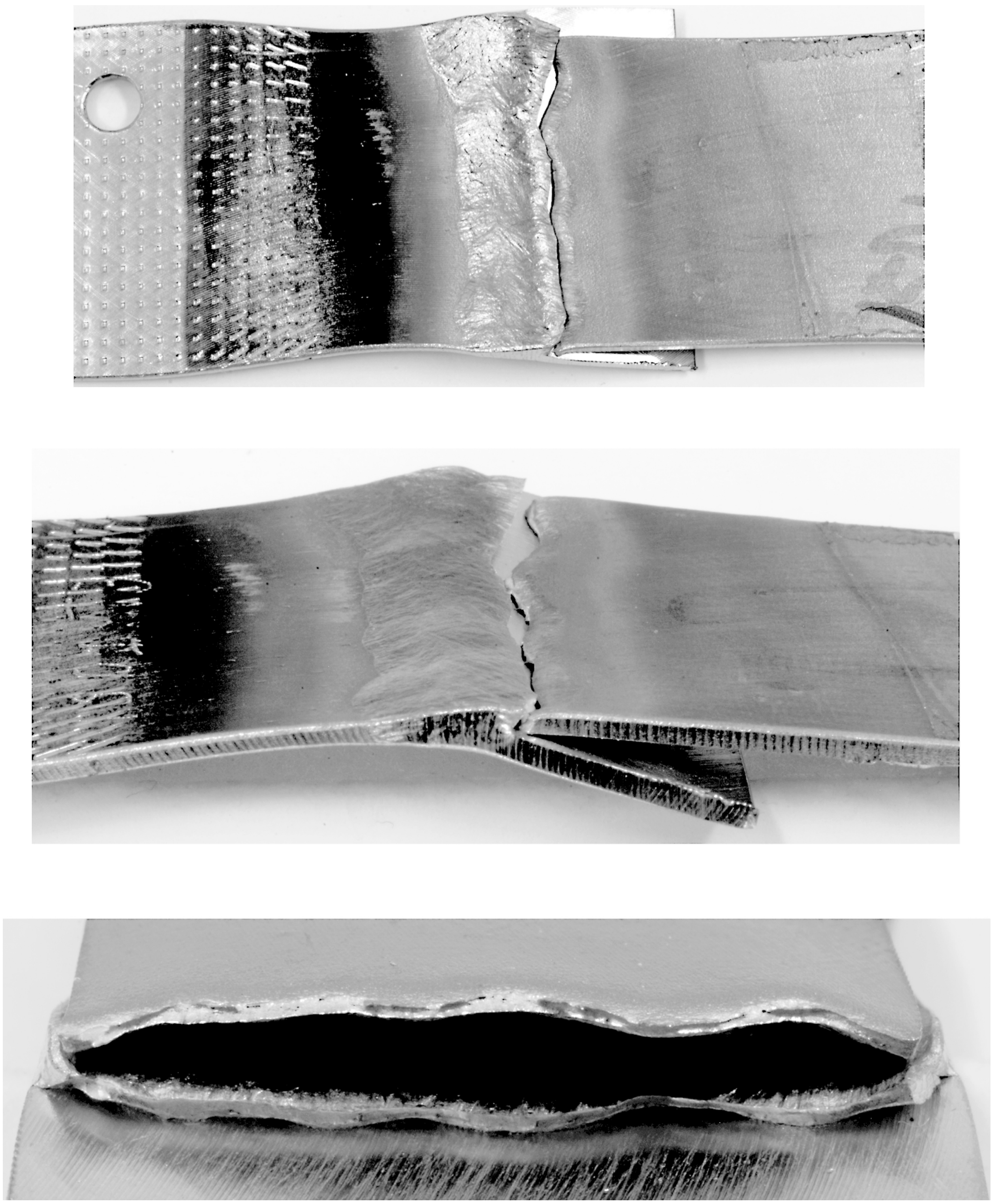
Figure 41 shows a butt weld joint on Al 5456, a configuration which included some of the most defective joints tested. This fracture revealed large voids, porosity, and lack of fusion.



26B3–T3

Figure 41. Al 5456 butt joint (test sample).

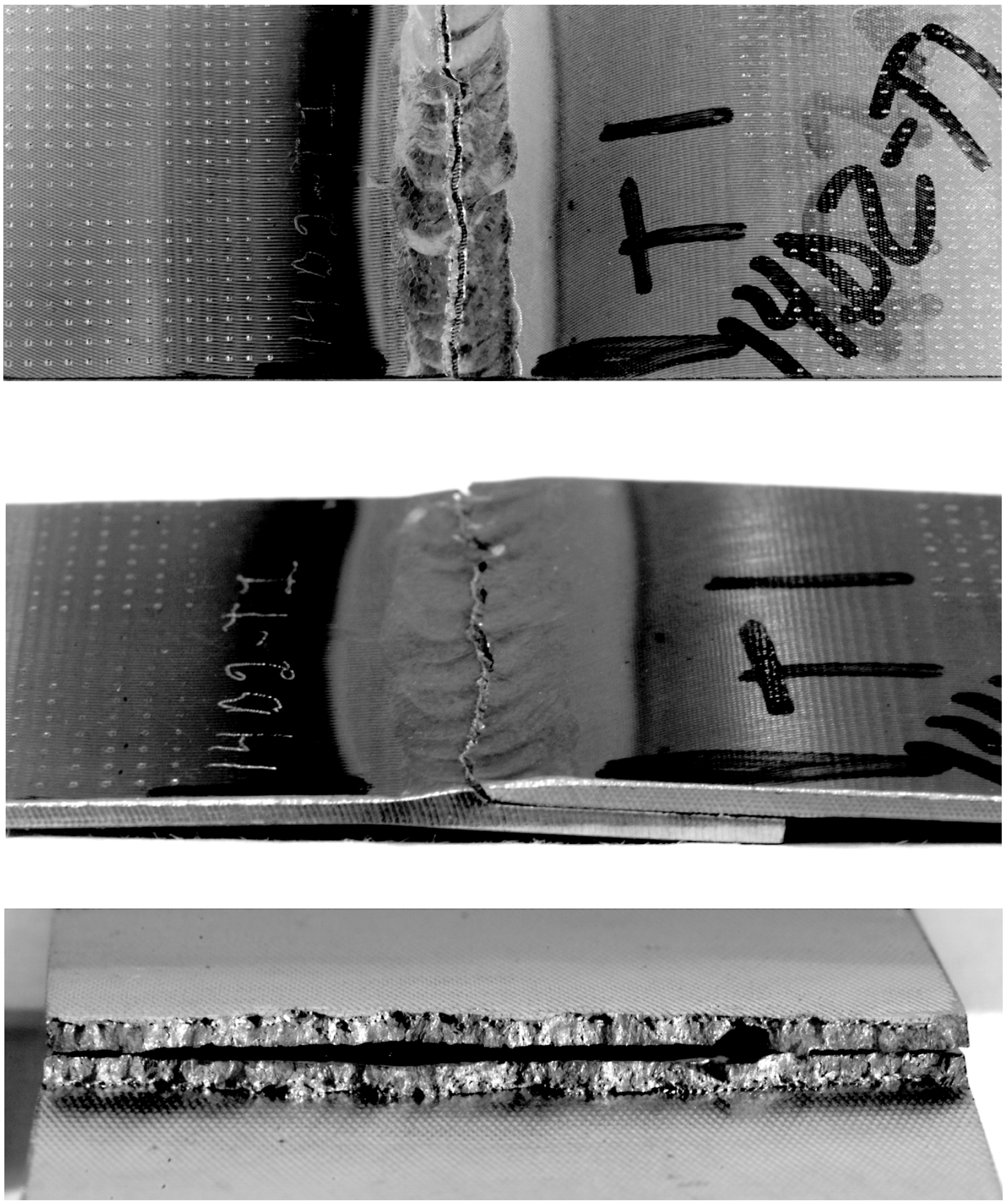
Figure 42 shows a lap fillet joint on 304 SS. It was one of the best samples tested, showing a clean fracture surface with no defects. It also showed some ductility from both the fracture surface and poor fit of the broken pieces.



15D1–T3

Figure 42. 304 SS lap/fillet joint (test sample).

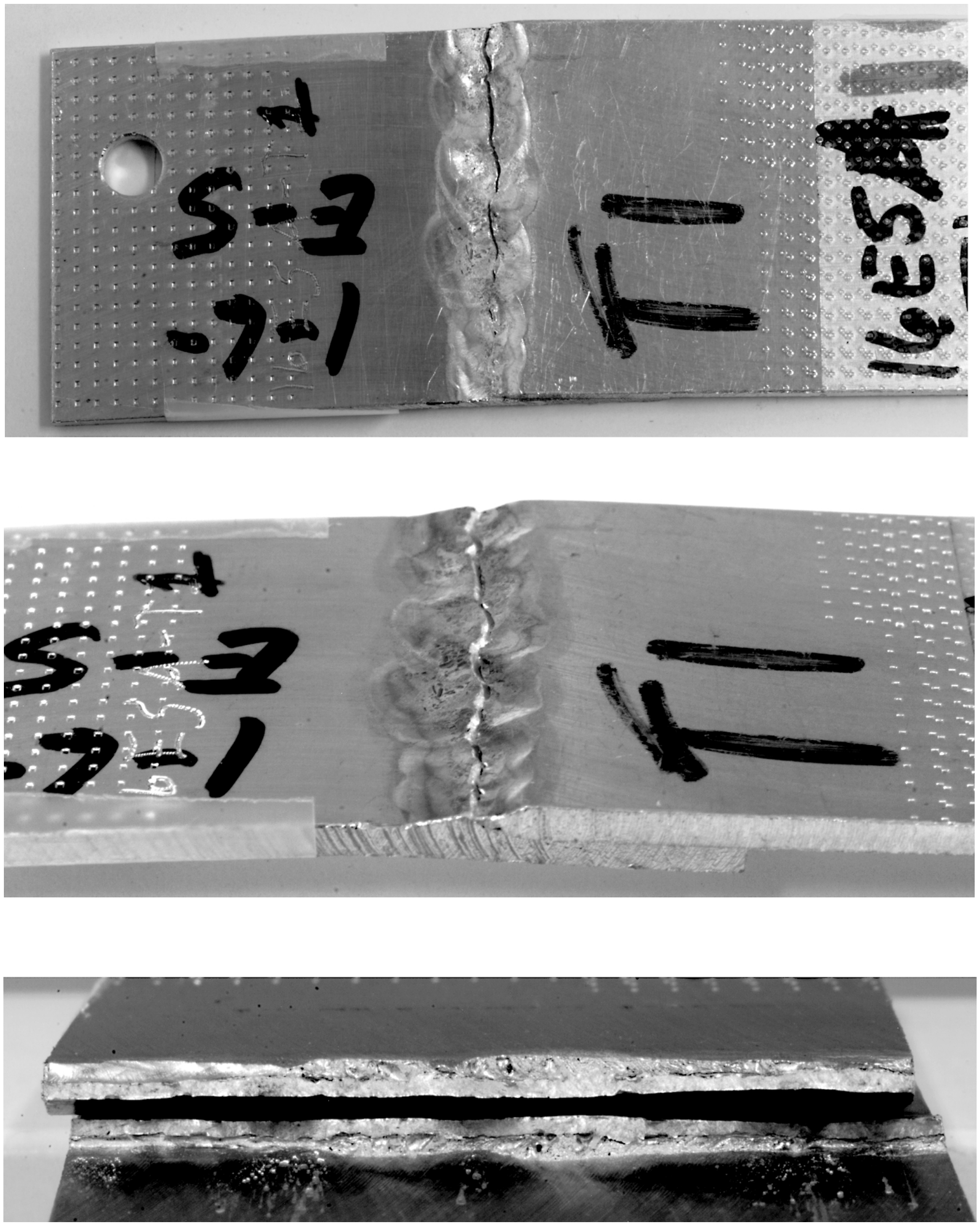
Figure 43 shows a lap fillet joint on Ti–6Al–4V. These samples were also good with clean fracture surfaces that showed no defects. However, their ductility was not as good as that of the 304 SS samples.



14D2–T1

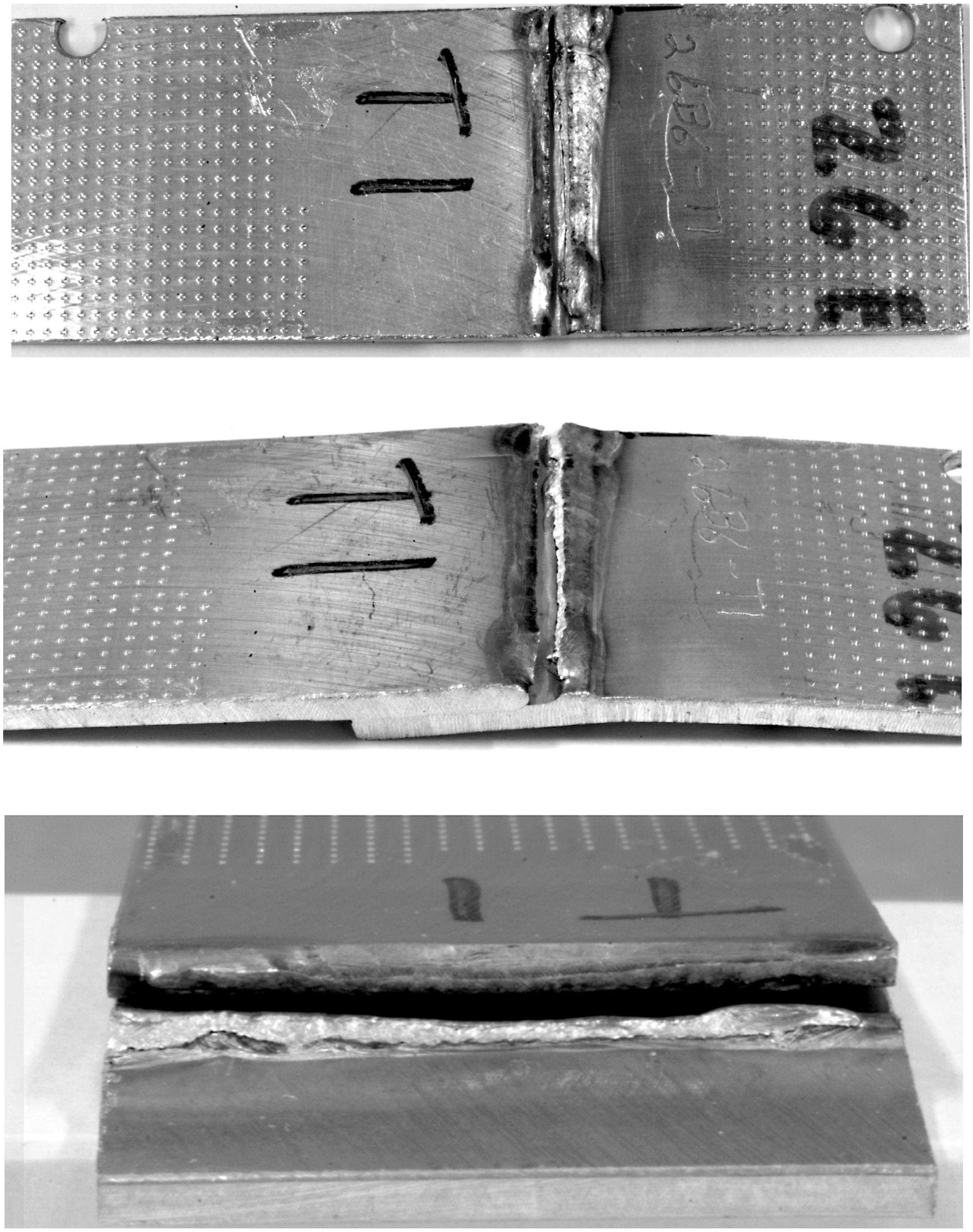
Figure 43. Ti–6Al–4V lap/fillet joint (test sample).

Figure 44 shows a lap fillet joint on Al 2219. Like the Al 2219 and 5456 butt joints, these joints were riddled with defects, mainly lack of fusion. Figure 45 shows the same to be true of the lap fillet joint on Al 5456. These defects were obvious to the unaided eye.



16E5A–T1

Figure 44. Al 2219 lap/fillet joint (test sample).



26B6–T1

Figure 45. Al 5456 lap/fillet joint (test sample).

3. EVALUATION OF REPAIR SIMULATION SAMPLES

3.1 Visual Examination

The remaining samples were used to represent actual repair scenario configurations. To simulate pinhole leaks, three holes were drilled through one wall each of 304 SS and Ti–6Al–4V tubing with 0.5-in diameters and 0.035-in thicknesses. The operators were asked to use the UHT to plug the holes. Two pinhole tube samples, both Ti–6Al–4V, were received from the training exercises. Upon visual examination, only one of the three holes in each tube appeared to have been successfully plug-welded (fig. 46). A second configuration of 304 SS tubing represented a tube-splice repair approach, using a brazed fitting technique (fig. 47).

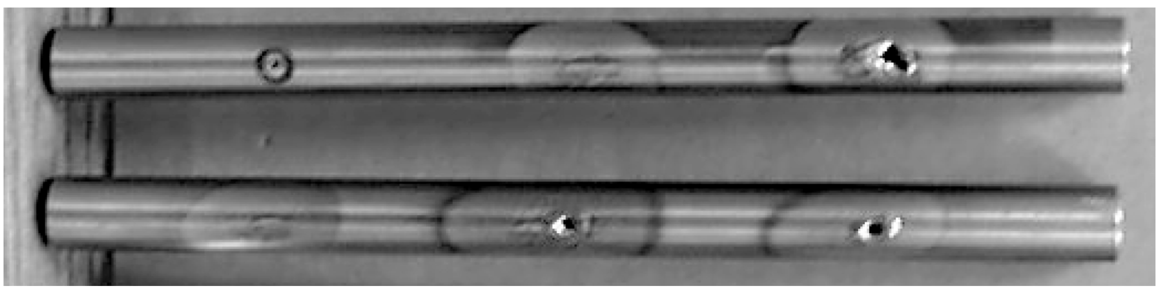


Figure 46. Ti–6Al–4V tube plug weld (test sample).

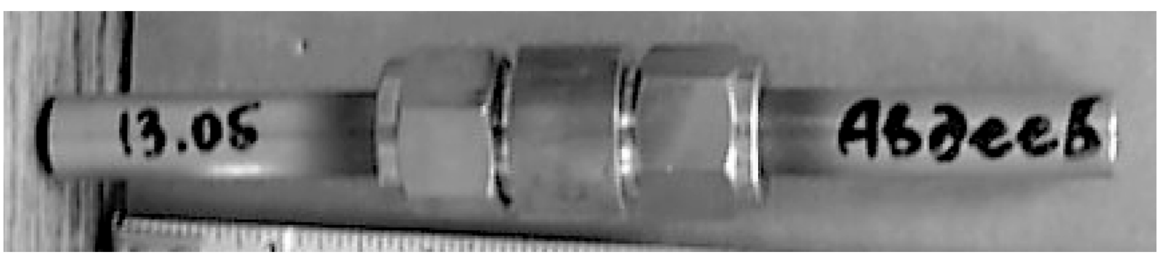


Figure 47. 304 SS tube braze (test sample).

The final samples simulated welding a patch to an *ISS* module and proved to be the most difficult to process. Two isogrids were made to scale. Al 2219 was used for the U.S. configuration and Al 5456 for the Russian configuration (figs. 48 and 49, respectively). A lap joint fillet weld configuration was used to weld both patches. Visual examination showed areas that lacked fusion around the circumference. The weld technique was made difficult in that the samples were in a fixed position, so that the operator could not get the best orientation to the joint and therefore had difficulty reaching some sides of the patch. The U.S. patch weld bead geometry was more uniform than that of the Russian patch. Positive weld bead reinforcement was evident around the whole perimeter, with localized areas of oxidation.

Although the Al 5456 sample was supposed to be welded with the filler wire handtool, it was finally welded without filler wire, as the operators found it impossible to orient the handtool and filler wire in the correct manner around all four sides of the patch. The weld bead was very inconsistent, with convex surface contour in areas.

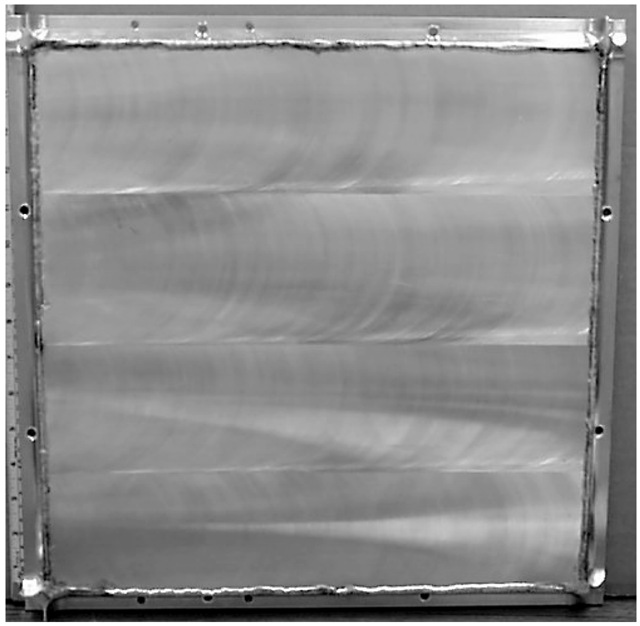


Figure 48. U.S. module simulated patch (test sample).

Figure 49. Russian module simulated patch (test sample).

3.2 Nondestructive Inspection

Radiographic examination of the tube plug weld samples on Ti–6Al–4V did not reveal volumetric flaws in the pinholes that were fused. Radiography was not conducted on the tube braze sample or the patch simulation samples, due to inherent difficulty in interpreting results for the joint configuration. Instead, both patch samples were penetrant-inspected and leak-tested to determine surface and through-thickness flaws. Both patch samples leaked at 15-psi air pressure. The U.S. patch, Al 2219, leaked at two of the four corners where the heat sink would have changed, making it difficult to achieve complete fusion. This patch had five other leak locations around the circumference, possibly at weld start/stop overlap areas. The Russian patch, Al 5456, had leak points at all four corners, along with four other leak points along three of the four sides. Apparently, the weld was too cold on these three sides, with most of the melting occurring on the patch instead of the module orthogrid legs. The fourth side did not leak and did not contain dye-penetrant indications.

4. CONCLUSIONS

The following conclusions were reached:

(1) Acceptable welds can be made using the UHT, despite the constraints imposed by a spacesuit and that the operators received minimal training prior to performing these welding operations.

(2) The lap joint fillet weld configuration was more suitable than the butt joint configuration for operators with limited welding skill. Achieving consistent full-penetration butt welds appeared to require more training and higher operator skill.

(3) Additional work is needed to determine the cause and possible corrective actions for the tendency toward porosity seen in Al welds made with the UHT. However, such porosity could have been due to lack of surface cleanliness or poor vacuum level.

(4) The U.S. module patch was found to be an acceptable design for welding with the UHT. However, the adequacy of the design as a repair approach could not be evaluated with the available sample due to localized leaking.

(5) Additional work is needed to develop an acceptable repair weld technique for the Russian module patch.

(6) The tube-braze joint configuration was designed by the PWI, and it was easily brazed in a repeatable manner. Repair of pinhole leaks was more difficult and may prove impractical for the level of skill typical of most astronauts and cosmonauts.

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13. ABSTRACT *(Maximum 200 words)*

The international space welding experiment was designed to evaluate the universal handtool (UHT) functions as a welding, brazing, coating, and cutting tool for in-space operations. The UHT is an electron beam welding system developed by the Paton Welding Institute (PWI), Kiev, Ukraine, and operated a 8 kV with up to 1 kW of power. In preparation for conducting the space welding experiment, cosmonauts were trained to properly operate the UHT and correctly process samples.

This Technical Memorandum presents the results of the destructive and nondestructive evaluation of the training samples made in Russia in 1998. It was concluded that acceptable welds can be made with the UHT despite the constraints imposed by a space suit. The lap joint fillet weld configuration was more suitable than the butt joint configuration for operators with limited welding experience. The tube braze joint configuration designed by the PWI was easily brazed in a repeatable manner.

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